

ASTRONET: Science Vision Update

Ian Robson



This is the update to the *ASTRONET Science Vision for European Astronomy* report that was published in 2007. The update is current as of February 2013. One of its key roles is to feed into the *ASTRONET Infrastructure Roadmap* update that will be published in late 2014.

ASTRONET was created by a group of European funding agencies in order to establish a strategic planning mechanism for all of European astronomy. It covers the whole astronomical domain, from the Sun and Solar System to the limits of the observable Universe, and from radioastronomy to gamma-rays and particles, on the ground as well as in space; but also theory and computing, outreach, training and recruitment of the vital human resources. And, importantly, **ASTRONET** aims to engage all astronomical communities and relevant funding agencies on the new map of Europe.

<http://www.astronet-eu.org/>

ASTRONET has been supported by the EC since 2005 as an ERA-NET. Despite the formidable challenges of establishing such a comprehensive plan, **ASTRONET** reached that goal with the publication of its *Infrastructure Roadmap* in November 2008. Building on this remarkable achievement, the present project will proceed to the implementation stage, a very significant new step towards the coordination and integration of European resources in the field.

Acknowledgements:

I would like to thank all those who contributed to this update of the Science Vision Document, especially those mentioned in Appendix 1. Ian Robson March 2013

'It is a pleasure to welcome the publication of this update which builds upon the very successful initial Science Vision. Thanks are due to all those who have contributed, particularly Professor Robson, and to the support of the EU FP7 programme. I hope that the Update will prove a useful and influential baseline for the on-going development of the European Astronomy and space science programme.' Dr Denis Mourard, **ASTRONET** Coordinator and Dr Ronald Stark, Chair **ASTRONET** Board



Cover image of the Flame Nebula in Orion taken with the VISTA telescope. Image courtesy of ESO/J.Emerson. Acknowledgement: the Cambridge Astronomical Survey Unit

ASTRONET: Science Vision Update 2012

Executive Summary

The Science Vision (SV) document was published in 2007 and as a relatively short time has passed since then it is of little surprise that the *key* issues and questions remain mostly unchanged, but make no mistake, a *lot* of progress has been made in tackling these big questions and there have been a number of changes to the SV that merit updating at a secondary level. These are described in this paper and the key points are presented here in the Executive Summary.

While the essence of the big questions in all the areas has not changed significantly since the publication of the SV, nevertheless, exciting results have emerged across many fields, especially as a result of new facilities such as Herschel, Planck, Kepler, Hinode, STEREO, Solar Dynamics Observatory, Pierre Auger Observatory, the first phase of ALMA, as well as ongoing programmes using existing facilities. The discovery of the filamentary structure of the interstellar medium in our Galaxy by Herschel has changed our views of the nature of star formation, while the spectacular spatial and temporal high-resolution images from the solar observatories have produced a whole new drive in understanding our Sun and how it interacts with the Earth and other planets through space weather.

Arguably, the most eye-catching new discoveries have come in the field of exoplanets, where the number has jumped from around 200 at the time of the publication of Science Vision to over 840 today. Not to be outdone, the fields of cosmology and the evolution of galaxies have made tremendous strides and the key aspect of ‘feedback’ is now fully recognised (although not understood). Dark Energy is now an accepted theme and there is a plethora of new and future instruments/surveys/missions to tackle this. Undoubtedly, the most significant development since 2007 in this area is ESA’s adoption of the Euclid mission, which will set the standard and context for much of ground-based cosmology over the next decade. It should also be recognized that the first major release of Planck results are expected in March 2013, and the timescale for SV revision and implications should allow for the main results from this event to be appreciated.

While not a part of the Science Vision, the huge success of the International Year of Astronomy 2009 (IYA2009 – by far the largest single science outreach project ever undertaken) created a major impetus for outreach expansion and citizen science. This has been followed up by the creation of the Office of Astronomy Development by the International Astronomical Union (IAU) along with funding to support outreach globally. A good example of the power of citizen science is now the expansion of web-sites allowing members of the public to work on science data and to make important contributions to the field. A recent example, also in the exoplanet domain, comes from the Planethunters.org project and the discovery of a planet in a quadruple star system.

For the most part the original Chairs/co-Chairs of the four SV Panels have produced the updates, with additional inputs from others and Members at Large. These individuals are

listed in Appendix 1 and this updating exercise will feed into the updating of the Infrastructure Roadmap that will begin in 2013.

Panel A: Do we understand the extremes of the universe?

Following the success of the Planck satellite, the thrust of CMB studies will move to the polarization domain to address the density and primordial gravitational wave signals. Gravitational wave astronomy suffered a setback with the non-selection of a large mission in the near future and it is likely that further focus will need to await the outcome of the LISA Pathfinder mission in 2014.

The search for the signatures of Dark Energy continues, with an increasingly open acceptance that such work also needs to consider modifications of theories of gravity as an alternative explanation for an accelerating universe. This field has been promoted to a new level of importance with ESA's adoption of the Euclid mission, scheduled for a 2020 launch. In the meantime, a range of new dark-energy experiments have been proposed – focusing on what can be achieved from the ground prior to Euclid. The latest observations from deep spectroscopic surveys (BOSS) have conclusively shown that acceleration took over from contraction of the Universe some 5-7 billion years ago. The search for Dark Matter continues but no conclusive results have yet been obtained from direct detection experiments. Indirect astrophysical detection via gamma-ray production due to WIMP annihilation has been an active area, yielding intriguing results from the Fermi satellite.

Progress continues in studying the regions around the black hole at the Centre of the Milky Way Galaxy and the latest millimetre VLBI experiments are starting to reveal details on the scale of the event horizon. These experiments will continue as long as the facilities remain and in due course may be taken on-board by an extended ALMA.

Panel B: How do galaxies form and evolve?

Impressive progress has taken place in the field of star formation in galaxies over the past five years thanks to extensive ground-based surveys combined with Spitzer, Herschel and HST data. It has been recognized that the vast majority of star-forming galaxies follow a tight star formation rate-to-stellar mass relation (then dubbed the Main Sequence of star-forming galaxies). Furthermore, they do so from the local Universe up to at least redshift ~ 2.5 . Outliers to the main sequence do exist as star-bursting galaxies, but only in small number and appear to provide only a marginal contribution to the global star formation density. Sub-mm observations at IRAM have revealed that star-forming galaxies at high redshifts are substantially more gas rich than their local counterparts, in accord with their higher star formation rates. Adaptive optics and integral field spectroscopy at the VLT have revealed that large rotating disks are common at redshifts around 2, and are characterized by a much higher velocity dispersion compared to local spirals.

The topic of star formation history from the dark ages to the present day requires different experimental techniques for investigation. Observations of the molecular gas and warm dust allow the star formation rate to be related to the gas content of galaxies, requiring infrared

through radio studies. Access to surveys in these regimes will be important as it is expected that using ALMA for surveys will not be an efficient use of such a valuable facility and that this should be the remit of less oversubscribed facilities such as IRAM and/or single-dish telescopes. ALMA will then focus on detailed follow-up of smaller sub-sets of objects offering an unbiased sampling of the galaxy parameter space.

Co-evolution of galaxies and their central supermassive black hole is now a central theme in galaxy evolution, together with the still debated processes that lead to the quenching of star formation in galaxies and the progressive emergence of the passively evolving population. The fraction of quenched galaxies appears to increase with both the stellar mass and with the local overdensity in which such galaxies reside, thus pointing to the existence of two (independent) quenching processes. AGN feedback may be one of such processes but this connection remains largely conjectural and how it would affect star formation and termination of further growth is still poorly understood and merits much more future study. Larger samples at each redshift are needed to define the demographics and hence further this topic. This requires 4 and 8m telescopes with dedicated surveys (and instruments such as multi-object spectrometers) with the necessary observing time to build-up the statistics, along with X-ray and radio data to identify those galaxies hosting an AGN.

Large photometric and spectroscopic surveys have also demonstrated to be very powerful tools for constraining the formation process of the Milky Way and of its various components, triggering N-body simulations to appreciate the relative effects of various scenarios. For example, it has been shown that several kinematic and chemical components are present in the Galactic Bulge and are associated with the various stellar populations present in the thin and thick disks. The two main scenarios for the bulge formation, a bulge component shaped by mergers and a population issued from the secular evolution of the Galactic disc, most probably co-exist, with the latter being predominant. Another example is the formation process of the thick disk and the respective weights and interactions between radial migration, disc instabilities driven by the bar and the spiral arms, and minor or major mergers, not to mention the still debated existence of the thick disk itself as an entity distinct from the thin disk. Finally, many streams have been discovered in the Galactic Halo, relics of past mergers in the Local Group, and a vast polar structure consisting of satellite galaxies of the Milky Way, globular clusters and streams have recently been discovered. A similar structure has been revealed surrounding Andromeda. Their interpretation may have far-reaching consequences on our understanding of the Local Group formation.

The need for Europe to maintain a competitive edge in Gaia follow-up means that it is extremely important that at least one of the proposed multiplex spectrometers is approved in the near future.

Panel C: What is the origin and fate of stars and planetary systems?

The overview is that all the considerations in SV Chapter 6 are still valid today, with the exception of the contribution expected from (sub)millimetre single dish telescopes. However, in terms of the details, there are a number of updates to be included, especially due to

Herschel, that has begun to produce transformational results in star formation. A new result is that for low-mass star forming regions the molecular cloud fragmentation process defines some of the major outcomes of the star formation process: the mass and spatial distribution of stars. This strongly suggests that in this mode of star formation dynamical interactions and feedback are secondary mechanisms.

Herschel has also shown the extreme filamentary structure of the interstellar medium, which implies that the processes leading to the fragmentation of clouds and production of cores seems to be mediated by the formation of filaments that become unstable and subsequently fragment into clumps. This will undoubtedly lead to follow-up campaigns with ground-based mm/submm telescopes.

A key question for the future is how much this view can also fit the high-mass star formation regime. It is clear that dynamical interactions in clusters have to play a significant role and exploring these systems at the same linear resolution (or better) as the nearby (low-mass) regions is a high requirement. This requires high resolution millimetre and submillimetre interferometry together with dynamical studies of resolved stellar populations.

While Kepler has made spectacular inroads into the discovery of exoplanets, with over 2,000 candidate systems now being discovered, this is far from the be-all-and-end-all of the subject of exoplanets and astrobiology. It remains the case that most of the Kepler discoveries are currently too faint for follow-up (and in many cases even confirmation). So while Kepler is giving us the sample statistics, brighter targets are needed for the follow-up to determine the key parameters of exoplanets. The search for Earth-like planets in the Habitable Zone remains the Holy Grail and recently Kepler has discovered the first example. Another discovery is that planets can exist in multiple systems (four parent stars being the current record) and from ground-based studies, the venerable HARPS instrument on ESO's La Silla observatory has just discovered a planet orbiting Alpha Centauri B, our closest stellar neighbour. Indeed, ground-based studies using transit-timing and micro-lensing have proved to be very successful for detecting exoplanets while radial velocity studies have made large inroads in the characterising of the exoplanets. It is confidently expected that continued operation of current or the development of future facilities/instruments will remain a high priority. The possible selection of CHEOPS by ESA is the next step in this direction. Gaia will bring an important contribution to the statistical knowledge of exoplanets by a systematic and unbiased astrometric monitoring of hundreds of thousands of main-sequence stars within about 200 pc, looking for the presence of giant planetary companions.

Panel D: How do we fit in?

The observations from Hinode, the two STEREO spacecraft and the Solar Dynamics Observatory have provided a new insight into the workings of our Sun; perhaps the most eye-catching new capabilities being the imaging of solar ejecta impacting the Earth and the high-resolution (spatial and temporal) imaging of the solar atmosphere. The data from these missions are still streaming in and this will keep the field fully occupied for a number of years. A natural next step is the study of the coupling between the Sun and the interplanetary

space from a distance sufficiently close to follow the consequences of solar surface processes in the Heliosphere. This is the main focus of the ESA/NASA Solar Orbiter mission (planned launch in 2017). The interplay between simulations and high (spatial and temporal) resolution studies of solar events is also making excellent progress and will be a key topic of consideration.

Significant progress has been made in the development of numerical simulations of the early history of the Solar System. Dynamical models strongly suggest that some migration of the giant planets has taken place in the early stages of their history, and we see traces of it, in particular, in the Late Heavy Bombardment. These results also illustrate the strong link between dynamical models of the Solar System and dynamical simulations of extrasolar planetary systems, where migration is believed to be a relatively common process.

The exploration of the terrestrial planets has seen a continuous progression with Messenger to Mercury, Venus Express to Venus, and numerous space missions to Mars. We should also remember that the Saturnian system continues to be explored by Cassini. In the future, the JUICE mission, recently selected by ESA for a launch in 2022, is designed for the exploration of the Jupiter system and will address, in particular, the question of its habitability. Our knowledge of comets should strongly benefit from the exploration of Comet Churyumov-Gerasimenko in 2014.

Astrobiology itself has made notable strides since SV, with wider cross-disciplinary attacks now being made. Indeed, the idea that we live in a 'bacterial Universe' is now almost taken for granted, but the step from this to complex life forms and the conditions and timescales that are needed to achieve this are now a focus of study using real data and better modelling.

Contents

Contents

Executive Summary.....	1
Contents.....	6
Chapter 1: Introduction	8
Chapter 2: Panel A - Do we Understand the Extremes of the Universe?	9
2.1: How did the Universe begin?	9
2.2: What is dark matter and dark energy?	9
2.3: Can we observe strong gravity in action?	10
2.4: How do supernovae and gamma-ray bursts work?	10
2.5: How do black hole accretion, jets and outflows operate?	11
2.6: What do we learn from energetic radiation and particles?.....	11
Chapter 3: Panel B - How do Galaxies Form and Evolve?	13
3.1: How did the Universe emerge from its Dark Ages?	13
3.2: How did the structure of the cosmic web evolve?	13
3.3: Where are most of the metals throughout cosmic time?	13
3.4: How were galaxies assembled?	14
3.5: How did our Galaxy form?	15
Chapter 4: Panel C - What is the Origin and Evolution of Stars and Planets?	16
4.1: How do stars form?.....	16
4.2: Do we understand stellar structure and evolution?	17
4.3: What is the life-cycle of the Interstellar Medium and Stars?	18
4.4: How do planetary systems form and evolve?.....	18
4.5: What is the diversity of planetary systems in the Galaxy?	19
4.6: Is there evidence for Life on exoplanets?	20
Chapter 5: Panel D - How do we fit in?	21
5.1: What can the Solar System teach us about astrophysical processes?	21
5.2: What drives Solar variability on all scales?	22
5.3: What is the impact of Solar activity on life on Earth?	23
5.4: What is the dynamical history of the Solar System?	24
5.5: What can we learn from Solar System exploration?	25
5.6: Where should we look for life in the Solar System?.....	27
Chapter 6: Recommendations	29

6.1: Cross Disciplinary Requirements.....	29
6.2: Do we understand the extremes of the Universe? (<i>from the original Science Vision</i>).....	29
6.2.1: Narrative update - 2013.....	30
6.3: How do galaxies form and evolve? (<i>from the original Science Vision</i>)	35
6.3.1: Narrative update - 2013.....	35
6.4: What is the origin and evolution of stars and planets? (<i>from the original Science Vision</i>)	43
6.4.1: Narrative update - 2013.....	43
6.5 How do we fit in? (from the original Science Vision).....	49
6.5.1 Narrative update – 2013	49
Appendix 1 Science Vision Update Contributors	57

Chapter 1: Introduction

This section has not been updated as such except to note that notable progress has been made on facilities and instrumentation. Indeed, in Fig 1.1 on p9, many of the ‘observatories under construction’ are now completed and operating (Herschel, Planck, Sofia, GTC, ALMA, VISTA, VST, LOFAR, Pierre Auger Observatory) and the rest are mostly close to completion or launch. The changes are listed below and current facilities/missions now operating/launched since the Science Vision publication include:

In space: Herschel, Planck, Hinode, STEREO, Solar Dynamics Observatory,

Airborne platforms: SOFIA

Ground-based: LOFAR, ALMA (now in reduced mode but fully operational in 2013), VISTA, VST, GTC, GREGOR (a German 1.5m solar telescope inaugurated in 2012 at Izana)

Current major instrumentation now includes:

X-Shooter (VLT); KMOS (VLT); SCUBA-2 (JCMT);

Funded Future Facilities can be updated by:

IRAM PdB upgrade to NOEMA; the LSST is now more certain in the USA; the Dark Energy Survey (DES) led by the USA but including Europe has begun construction; in Europe the Next Generation Transit Telescope is now well under way although not fully funded; eROSITA (medium-energy X-ray all-sky survey telescope on the Spectrum-Roentgen-Gamma satellite) is due for launch in 2014.

Funded Future ESA Facilities can be updated by:

The selection of the next M-class missions of *Solar Orbiter* and *EUCLID* with launches in 2017 and 2019 respectively, and the L mission, *JUICE*, to be launched in 2022. This has ramifications for the three missions not selected, i.e. *PLATO* for the M-class and the two L-class missions of *NGO* (the New Gravitational wave Observatory) and *ATHENA* (the Advanced Telescope for High Energy Astrophysics - in previous incarnations as Xeus/IXUS). *Cheops* (Characterising ExOPlanet Satellite) is now funded (with Switzerland) as an ESA Small Mission.

The situation for *SPICA* as a special mission with Japan remains unclear.

ESA’s pool for the following M-class mission due to be launched in 2020-2022 contains: *EcHO* - the Exoplanet Characterisation Observatory; *LOFT* - the Large Observatory for X-ray Timing; *Marco-Polo-R* for an asteroid sample-return; and *STE-QUEST* - the Space-Time Explorer and Quantum Equivalence Principle Space Test mission and *PLATO* – to complete a census of exoplanets around nearby and bright stars.

Chapter 2: Panel A - Do we Understand the Extremes of the Universe?

2.1: How did the Universe begin?

On p19 the latest data from WMAP have indeed hinted more towards a tilt of the power spectrum as a result of inflation with the modified the value of the spectral index now being $n_s = 0.968 \pm 0.012$ rather than 0.95 ± 0.02 . Within the past few days, data from the SPT has improved this to an amazing figure of 0.9538 ± 0.0081 and Planck will soon do better still.

On p20 the comments about the CMB now point more strongly to the need for Planck to be followed up by an all-sky polarisation mapping machine.

2.2: What is dark matter and dark energy?

This topic remains at the forefront of current research and forms the basis for a number of upcoming or planned experiments/missions.

On p21, we should note for completeness that while the recent observations have led to the amazing conclusion that the Universe is dominated by a uniformly distributed form of (dark) energy that behaves as Einstein's cosmological constant Λ , this does assume that Einstein's theory of gravity applies on the largest scales. This then flows into p22 where it would be better to say that 'One of the most pleasing developments in modern cosmology is, therefore, a new focus on testing Einstein's theory of gravity, rather than simply assuming its correctness. The hypothesis that dark energy is an artefact of using the wrong theory of gravity can be distinguished by measuring the growth rates of supercluster-scale density perturbations, and so far these are consistent with standard gravity (<http://arxiv.org/abs/1106.2476>). Nevertheless, searching for modifications of gravity will be perhaps the most important goal for future cosmological experiments, in particular ESA's Euclid satellite'.

Regarding the section on experimental signatures, it should be noted that the Fermi Gamma-ray Space Telescope has recently announced the observation of an intriguing signal at around 130GeV from the Galactic Centre that *might* be the result of dark matter annihilation (<http://arxiv.org/abs/1206.1616>). It is clear that the search for dark matter signatures remains high on the wish list of experiments.

In the section on Future Strategy it should be noted that Planck has now measured the pattern of the CMB to effectively perfect precision as far as the temperature pattern is concerned (page23). Additionally, regarding gravitational lensing, this will be a central part of the programme of ESA's Euclid satellite, although ground-based colours will still be required. Possible approaches to obtaining this information continue to be to construct a very large CCD imager (or to collaborate in a US-led experiment such as the forthcoming LSST).

In terms of the large-scale structure and clusters of galaxies constraint on dark energy, the notion of addressing the mass function of clusters and their baryon fraction as determined for $> 100,000$ clusters, best selected from an all-sky X-ray survey (eROSITA?) has a double

impact as such surveys can also give important information on peculiar velocities from redshift-space distortions of clustering, which is a direct route to detecting modifications of gravity. Again, ESA's Euclid satellite will make heavy use of this method.

2.3: Can we observe strong gravity in action?

More data now point to the mass of the black hole in the centre of our Galaxy to be greater than 4 million rather than 3 million solar masses (p27) and in fig 2.5 on p28, these data have allowed an updated orbit of the S2 star plus the highly eccentric gas cloud falling in towards the Centre to be observed (i.e. Fig. 1 of Gillesen et al, Nature 481, 51–54, 2012).

In section 2.3.2 on p28, good progress with VLBI has been made and new observations using mm VLBI (1.3 mm) of the Galactic Centre have been achieved and these reveal structure on scales comparable to the event horizon (see e.g. Fish et al 2011, ApJ 727, L36). Furthermore, in regard to Sgr A*, flaring activity is observed in both X-rays, infrared and radio on time-scales of less than hours, thereby probing activity within 10's of Schwarzschild radii.

Also on p28 and elsewhere in SV, the mention of 'a 1 km² collecting area radio telescope' should now just be changed to SKA.

Fig. 2.6 on p29 could now also be updated using the ionized iron L and K emissions peak spectrum from the Seyfert 1 galaxy 1H 0707-495 from Fabian *et al Nature* **459**, 540-542 (2009). The standard view is that this feature, together with the time variability, provides strong evidence that we are witnessing emission from matter within a gravitational radius, or a fraction of a light minute from the event horizon of a rapidly spinning, massive black hole. However, recently this classical argument has been thrown into some doubt by questions as to the origin of the red-tail, and that rather than this being an indicator of strong-gravity near to a black hole, it may be a result of incorrect (i.e. too simplistic) assumptions about the smoothness of the absorbing column (e.g. <http://arxiv.org/abs/0907.3114>).

Also on p29 the ESA decisions regarding the proposed missions XEUS and Constellation-X' needs to be noted and carried forward into the Infrastructure Roadmap.

2.4: How do supernovae and gamma-ray bursts work?

On p30 we need to change the statement 'No single simulation has so far provided the required explosion energies from first principles for either class, and many questions regarding the explosion mechanisms remain open (Figure 2.7)' to 'Although simulations can reproduce many of the basic features of both types of explosion, no single simulation including both the necessary three dimensional effects and fully consistent physics has been presented. For core collapse supernovae the neutrino physics and interactions are crucial, while the detailed physics of the flame propagation and detonation is not yet understood for the thermonuclear supernovae'.

Also, instead of 'The lack of any secure progenitor system for thermonuclear supernovae is one of the most critical impediments for their application as distance indicators and resolving this problem will consequently also have wide-ranging consequences for cosmology (§

2.2.1).’ we can now better say ‘Although important constraints on the progenitor systems have recently been obtained from nearby thermonuclear supernovae, the lack of any secure progenitor system is one of the most critical impediments for their application as distance indicators. In addition, an understanding of systematic effects due to e.g., metallicity and host environment, is necessary for their use as precision probes of cosmology (§ 2.2.1)’.

For the description of the core-collapse supernovae on p32, we now know a little more about the fundamental questions and we can add that there is still a dearth of observations of progenitor objects, especially for the high mass end and ask which of these collapse to black holes, which to neutron stars and what is the nature of the recently discovered super-luminous supernovae.

Regarding gamma-ray bursts and the formation of a possible accretion disk and jet (p32) we also need to understand the signature of different kinds of compact binary mergers for the short gamma-ray bursts.

On p33 after the SN1987A it is now appropriate to add that future sky surveys (like LSST), as well as the ongoing searches with the Palomar Transient Factory, PanSTARRS and the large effort in follow-up (e.g. the >400 NTT nights with PESSTO) will discover thousands of nearby and distant supernovae. In particular, rare types of supernovae will most likely be found, many at faint and at high redshifts. The distant, super-luminous supernovae, recently discovered, represent but one example. Efficient follow-up of these candidates require access to both 8-10m class telescopes and for detailed studies an E-ELT. This is particularly true for supernovae at redshifts greater than two, where a handful of UV bright objects have been discovered, but no detailed studies have yet been possible.

On p34, the potential effects of rotation and magnetic field also need to be embraced in the core-collapse simulations, making the need for access to supercomputer facilities even more necessary.

2.5: How do black hole accretion, jets and outflows operate?

The Fermi Gamma-ray Observatory (previously known as GLAST and launched in 2008) has provided a wealth of data on the flaring behaviour of blazars, detecting far more than previous gamma-ray studies. These data, along with multi-wavelength studies of the evolution of the flares will provide more stringent constraints on relativistic jet models from the supermassive black hole.

2.6: What do we learn from energetic radiation and particles?

Fermi has also shown that in spite of the above observations, only about 30% of the gamma-ray background comes from AGN, which was a surprise. Where the remaining 70% originates is now a topic of intense study.

Data from the Pierre Auger Observatory, now in operation in Argentina and the Telescope Array (in Utah) have made notable inroads into this section. However, the fundamental questions about origins of the ultra-high energy cosmic rays and the shape of the spectrum

around the expected cut-off still remain tantalising elusive. The data now strongly support a power-law spectrum up to ~a few times 10^{18} eV and a definite steepening above 5×10^{19} eV; in between there is an inflection that is not understood. However, we know that sources in the Galaxy cannot accelerate particles beyond about 10^{18} eV and quite apart from the physical limitations for plausible sources, gross anisotropies should then be seen since the Galactic magnetic field is far too weak to randomise the directions of such particles. These are not seen.

The cutoff at $\sim 10^{20}$ eV is consistent with the ‘Greisen-Zatsepin-Kuzmin’ effect, caused by the interactions of the cosmic rays (if these are protons) with the CMB. However, to show that what is seen really is the GZK cutoff requires better statistics and a determination of the composition.

Intriguing observations seem to indicate an anisotropic distribution of the ~ 100 events above 5×10^{19} eV so far observed by Auger and the Telescope Array but associations with different classes of extragalactic sources remains highly controversial and awaits better statistics from further observations.

We should note that the site for the northern hemisphere counterpart of Auger has been selected in Colorado.

Chapter 3: Panel B - How do Galaxies Form and Evolve?

There have been significant changes in this topic since SV primarily driven by observations at new and existing facilities. One major update concerns the generic topic of star formation and although some of this material is covered in the current sections, it would be beneficial to produce an entirely new section focusing on ‘Star Formation over cosmic time’. This would cover aspects such as determining the connections over cosmic time between gas accretion and accumulation, star formation, galactic winds, metal enrichment, black hole growth and the ultimate quenching of star formation in massive galaxies. Updating of the general introduction needs to expand on these issues and address such topics as the first gamma-ray bursters (GRBs) and the contribution of the warm-hot phase to the baryonic census.

3.1: How did the Universe emerge from its Dark Ages?

The observation of many more GRBs is shedding new insights into the very early Universe through the now-mature system of rapid ground-based follow-up and redshift determination. More examples can be expected to follow, which will eventually lead to meaningful statistical conclusions about the star formation and evolution in the very early Universe, albeit once the nature of GRBs themselves is better understood through more observations and detailed follow-up with 8-10m telescopes.

Mention should also be made of the major progress that has been made in the direct observations of galaxies in the reionization era. Thanks to the installation of the Wide Field Camera 3 (WFC3) on the HST during the final (2009) servicing mission, we now have firm detections of galaxies up to redshift 9, with candidate objects up to redshift 12 (arXiv:1102.4881 and a set of papers from the CANDELS collaboration due to appear over the next month).

3.2: How did the structure of the cosmic web evolve?

In the background (3.2.1) to this section we can now include the super massive/multiple galaxy cluster discoveries by Planck.

While most of the Key Questions and Experiments of section 3.2.2 remain sound, the searches for (candidate) clusters at $z \sim 1-2$ requires some updating as well as the latest results on the successful SZ searches and the mapping of dark matter in clusters through gravitational lensing.

3.3: Where are most of the metals throughout cosmic time?

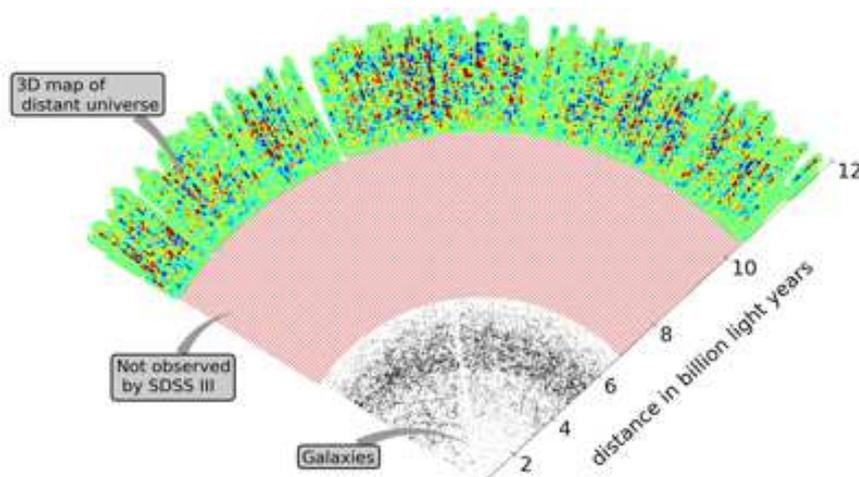
The evolution of the IGM metallicity between $z \sim 2-6$ discussed in 3.3.1(p53) requires some updating in light of observation. Also, new data has shed greater light on the epoch of the peak activity of galaxy and quasar formation in 3.3.2 and it would be beneficial to add a short discussion on the contribution of circumgalactic medium to the metal census and its relationship with superwinds through current surveys being done at $z \sim 3$. Also an update of the census of cosmic baryons (through the COS results) in the Local Universe is required (p55).

3.4: How were galaxies assembled?

The Sloan Digital Sky Survey (SDSS) continues to make major inroads into this field (p57) and mention should be made of the results from the Baryon Oscillation Spectroscopic Survey (BOSS) and its goals as a major contributor. The latest data release in 2012 from 250,000 distant galaxies has confirmed the time when Dark Energy overcame gravity as being between 5-7 billion years ago.

Major novelties have come from large surveys at 8-10m class telescopes coupled with space data, especially from the HST, Spitzer and Herschel. IRAM has pushed to redshift ~ 2 the census of molecular gas in galaxies, allowing the link to their star formation rates from continuum studies of dust emission. The result is that the gas-consumption time-scales are so short that galaxies need to be continuously replenished in order to maintain their star formation rates.

On the theoretical side, we have seen a paradigm shift from merging as the main driver of galaxy evolution to quasi-steady accretion through 'cold streams'. However, this process remains observationally elusive whereas evidence of large-scale galactic winds is ubiquitous. The question of the intimacy between the growth of black holes and galactic bulges (i.e the galaxy-black hole co-evolution) has made notable strides since the SV document. AGN feedback is now widely entertained as a way to quench star formation in galaxies, subsequently turning them into passively evolving structures. However, the exact nature of how AGNs interact with the galactic gas and star formation is still unclear. This is an area where computer simulations have made great strides but are still dependent on more detailed observational data that need 8m telescope time.



This map shows a slice through the 3D map created by Slosar and his team with BOSS, with red highlighting regions with more gas; blue with less gas. The cross-hatched areas are those not observed by BOSS. We are at the bottom tip of the wedge, looking out through individual galaxies into these distant gas clouds illuminated by quasars, spectacularly bright sources of light created by material flowing into black holes. Image: Slosar and the SDSS-III collaboration.

For future observations the ESA decision on EUCLID is crucially important. This will lead to detecting resolved stellar populations in the Local Universe; the detection/measurement of the cold gas properties of high- z galaxies, detailed mapping of gas, star formation as well as making major inroads into the star formation laws in nearby galaxies.

3.5: How did our Galaxy form?

This section mostly stands as is but there has been progress in that large photometric and spectrometric surveys such as SDSS and APOGEE, RAVE, AAOmega and others, together with the development of numerical models, are being extensively used to understand better the formation and evolution of our Galaxy and of its various components. Observations have revealed many streams of ‘fossils’ indicating minor mergers in the distant past, several stellar populations in the Galactic Bulge, the effect of stellar migration in the Galactic Thick Disc, among other results. The missing fundamental data, i.e. accurate distances and proper motions, will be provided by the systematic census that will be performed by GAIA in the coming years. Also, good progress has been made from detailed spectroscopic observations measuring the abundances in individual stars of Local Group dwarf galaxies. In the section on Future Experiments (3.5.3) mention should now be made of the various proposed Gaia spectroscopic survey follow-ups, such as from ESO and other telescopes. It is critical that at least one of the proposed spectroscopic instruments for follow-up is supported and this needs to be taken on-board in the Infrastructure Roadmapping as a matter of urgency.

Chapter 4: Panel C - What is the Origin and Evolution of Stars and Planets?

Most of the key science and questions in this chapter remain valid today; the most notable exception is the exoplanet field, which has been expanding at an incredible rate with revolutionary results coming from the high precision radial velocity surveys, direct imaging campaigns and transit detections from space. These dramatic advances imply that the questions that need to be addressed in the coming five to ten years are partly different to those reported in the SV. There has been significant progress in the deployment of the infrastructures that will help answering some of the questions in the other fields covered in this chapter, but it is still too early for most of them to produce significant shifts in the key questions.

4.1: How do stars form?

Herschel has started to produce transformational results in this area, but much of these still need to be properly digested. However, what seems to come out of the Herschel surveys is that in nearby low-mass star forming regions, the molecular cloud fragmentation process defines some of the major outcomes of the star formation process: the mass and spatial distribution of stars. Both these results have a profound implication on our understanding of the star formation process and suggest that in this mode of star formation dynamical interactions and feedback are secondary mechanisms. A clear prediction that needs to be addressed in the future is that the velocity dispersion of young stars is also directly related to the velocity dispersion of the parental cores. This will have to be tested by deriving detailed measurements of the velocity dispersions of the young stellar objects and of the prestellar cores.

The data also imply that the processes leading to the fragmentation of clouds and production of cores seems to be mediated by the formation of filaments that become unstable and subsequently fragment into clumps. The kinematical and physical relationship between the cores and filaments needs to be explored in detail and is a key topic for future high angular resolution millimetre and submillimetre observations. Here, it is clear that ALMA will play a key role in the determination of the physical parameters of cores (kinematics, magnetic field, chemistry) and their relationship to filaments. High precision optical/infrared high resolution spectroscopy combined with Gaia distances will be key to study the dynamics of young stellar objects.



Herschel 70-250 μ m maps of the DR21 region showing the finely detailed and filamentary structure of the cold ISM (courtesy of ESA/PACS and Spire consortium).

A key question for the future is how much this view can also fit the high-mass star formation regime. It is clear that dynamical interactions in clusters have to play a significant role and exploring these systems at the same linear resolution (or better) as the nearby (low-mass) regions is a high requirement. This requires high resolution millimetre and submillimetre interferometry together with dynamical studies of resolved stellar populations, i.e. ALMA.

4.2: Do we understand stellar structure and evolution?

This section remains mostly unchanged and major new results are expected in the future, especially from the Gaia mission. On the other hand, Corot and Kepler have started to provide some of the detailed databases for studies of variability and the VLTI has produced some interesting results on nearby stars.

One area that will probably expand in the future with high precision and high resolution spectropolarimetry is the study of magnetic fields as a function of stellar parameters and age.

On the modelling side, progress on our understanding of pre-main sequence evolution remains limited. Recent efforts have established the importance of the history of accretion during the first part of stellar evolution, but observationally very little constraints are available. On the other hand, submillimetre studies have shown that the Class 0 protostars

seem to mimic the Initial Mass Function – begging the questions as to what drives this selection (see 4.1 above). This will be a key point to address in the future.

4.3: What is the life-cycle of the Interstellar Medium and Stars?

This is the realm of ALMA and we can expect significant progress to be made in the areas of the chemical properties of individual protostars and the chemistry of complex organic molecules in the interstellar medium. Most of this part of the original Science Vision document is still valid today. The major developments in the recent years have been in the study of water chemistry, again, using Herschel. While the results are still preliminary, we now have a better picture of the role of water, CO and OH as coolants and tracers of shocks and radiation heating in outflows.

Herschel has revealed rather dramatically that the observations of outflows from the late stages of stars are to a large extent shaped by the interactions between these outflows and the interstellar medium. This does not make life easier, but on the other hand is revealing for both mass loss processes and the conditions in the ISM. Again, ALMA is the way to disentangle these effects, with its angular resolution and molecular diagnostics on composition and dynamics.

Studies of late-type stars and supernovae, in their role as sources of heavy elements and complex molecules for the ISM, are also being investigated using Herschel, and at high angular resolution with ALMA. In particular, the clear detection of dust and molecules in the ejecta of SN1987A is going to set strong constraints on the supernovae yields. ALMA has also started to produce very high sensitivity, spatially resolved observations of late-type stars and much is expected in this area in the coming years, also in combination with mid-IR JWST observations.

A novel insight into stellar and planetary evolution has come about due to clues as to the long-standing puzzle of the ‘anomalous spectra’ of some white dwarfs. Whereas models confidently predict that the spectra should be either hydrogen or helium, some white dwarfs were known to have metal contaminants. Recent observations from Spitzer have shown that 1-3% of all white dwarfs have an infrared excess, which has been shown in some cases to be silicate based. The solution seems to be that the heavy elements arise from tidal disruption of asteroid belt objects by the white dwarf itself, and hence the ‘contaminants’ represent the debris from the surrounding planetary systems. By measuring the heavy elements using 8-10m telescopes estimates can be made of the amount of surrounding material and hence the pre-white dwarf status of a planetary system.

4.4: How do planetary systems form and evolve?

A lot of progress has been made since SV in the characterization of the timescales for the evolution and dissipation of protoplanetary disks. It is now clear that planet formation has to occur in the first few Myr of the life of a star. Models and observations of the evolution of

solids have been developed and there is now a general consensus that the core accretion scenario is the most viable mechanism for the formation of planetary systems. However, key questions regarding the timescales for growth and transport of solids and gas in the disk still need to be answered as the observations seem to be at odds with model predictions. The VLA (now the Jansky Very Large Array – JVLA) and ALMA have already started to play an important role, especially in resolving the radial distribution of solids in disks and this will continue for the foreseeable future. In the distant future, the high frequency component of the SKA will allow study of the evolution of solids as the disks evolve and dissipate.

Regarding the study of the gas in disks, significant progress is expected from ALMA, while Herschel has had several programs focusing on studying the gas in protoplanetary disks. However, the results have not been as revolutionary as initially hoped, mainly because the gas emission in the Herschel bands has turned out to be much fainter than expected. This, of course, is an interesting result in itself. Indeed, one of the most intriguing findings from Herschel is the low emission from cold water vapour in protoplanetary disks. These initial findings will have to be followed up and extended with ALMA.

The development of detailed models of the chemistry of disks emanating from the Herschel and millimetre interferometer programs has allowed the European community to develop essential tools that will be essential in the analysis of ALMA and NOEMA data. Direct imaging of disks with extreme adaptive optics at large optical/infrared telescopes (VLTI) is also starting to produce essential constraints that are complementary to the millimetre observations. Much is expected to be achieved from the combination of different observing techniques that are both starting to allow probing of the planet formation zone of disks in the 5-10 AU range.

4.5: What is the diversity of planetary systems in the Galaxy?

The discovery and characterisation of exoplanets is the topic within SV that has changed most in the last five years. The population of gaseous giants have been enormously expanded, but the real breakthroughs have been the detection of Neptune-mass and few Earth mass planets in large numbers and also in multiple systems. The Holy Grail of finding an Earth-like planet in the habitable zone remains and the recent discovery of a few times Earth-mass sized planet (super-Earth) in the habitable zone shows the promise for the future. Indeed, the recent detection of an Earth-mass planet in the Alpha Centauri system is just the cherry on top of the huge advance in the field. These discoveries owe their success to the radial velocity surveys, mostly carried out with the HARPS spectrograph at the ESO 3.6m telescope. It is clear that radial velocity surveys with increasing accuracy are still essential for this field and will continue to be for a long time – as shown by the production of the HARPS-North instrument.

Direct detection techniques has also started to contribute significantly in recent years and the arrival of SPHERE at the VLT will certainly be a major milestone in the short-term. Corot

and Kepler have fulfilled their promise and discovered a very large number of transiting planet candidates; unfortunately, spectroscopic follow-up is very difficult for most of the sample of Kepler stars due to their faintness. A wider area surveyor that will target brighter stars is needed for the future and the Plato mission could fill this gap nicely. Astrometric searches also remain a promise for the future and Gaia's main contribution to exoplanet discovery will be its unbiased census of planetary systems orbiting hundreds of thousands of nearby relatively bright main-sequence stars: all stars brighter than about 13 magnitude of all spectral types within about 200 pc will be screened for 5 years with constant astrometric sensitivity. Besides a significant input to the statistical knowledge of the properties of exoplanets, Gaia will provide suitable nearby targets for further detailed observation such as direct detection and spectral characterization.

4.6: Is there evidence for Life on exoplanets?

Not unexpectedly, very little progress has been made on this topic and the arguments remain unchanged. However, the potential has been shown to be sound with more detailed experiments looking at the reflected Earth spectrum being carried out with the aim of identifying the signature of life. However, overall this topic remains severely photon starved and most of the hopes still rest in direct spectroscopic observations with the E-ELT.

The study of exoplanet atmospheres has mostly been developed using on-off transit techniques. The hints of success from Spitzer data are a driver for future JWST programs, but also for dedicated mission proposals such as ECHO, while advances are also to be expected from ground-based programs. Most of the effort has been devoted in designing specific missions to observe planetary atmospheres for transiting planets; this has proven successful with the very recent ESA announcement of the support for Cheops (Characterising ExOPlanet Satellite) for a launch in 2017 as a Small Mission to search for super-Earths to Neptune-sized bodies. Downstream, ECHO will also be a major mission in this quest.

Chapter 5: Panel D - How do we fit in?

Chapter 5 has stood the test of time well in most of the areas but on the solar atmosphere and heliosphere/space weather fronts there have been several major strides in scientific research since the SV, specifically due to the space missions of: Hinode (launched 2006), STEREO (2006) and the Solar Dynamics Observatory (2010). All are still fully operational and provide the following:

- High-resolution (spatial and temporal) imaging and spectroscopy, in particular in the extreme-UV, and magnetic (photospheric) imaging, of the Sun - allowing detailed studies of the fine-scale structures of the chromosphere and corona. (Hinode, SDO).
- First imaging of solar coronal mass ejections (CMEs) from out of the Sun-Earth line, using spacecraft ahead and behind the Earth – to identify and track CMEs from Sun to Earth and study their propagation and impact. (STEREO).
- The first ever stereoscopic imaging of a star - the Sun, using twin EUV images from the widely-spaced STEREO spacecraft – allowing 3D magnetic modelling of solar active regions in particular (STEREO).
- The first ever imaging of a complete star (in EUV) using the two STEREO spacecraft (from February 2011) and, later, with the STEREO and SDO spacecraft combined – allowing global studies of the solar atmosphere (STEREO, SDO).

5.1: What can the Solar System teach us about astrophysical processes?

Section 5.1.1, page 101, bottom paragraph refers to the fine-scale EUV observations made of the solar atmosphere and mentions SOHO (still operational) and TRACE (now terminated). These have now been augmented by new spacecraft (see above) and unprecedented fine-scale observations of the EUV with SOHO, Hinode, STEREO and SDO are now available. These have served to demonstrate the true, highly-dynamic, complex fine-scale magnetic structure of the low solar atmosphere.

On p102, the SV discussed the fine-scale, low solar atmosphere – and the spacecraft observations using SOHO and TRACE at that time. It moves on to talk about the near-Earth environment and, particularly Cluster observations. In 2007 there was a dearth of experience of the space between the Sun and the near-Earth environment, but the situation has improved dramatically as a result of the new facilities. We now have extensive heliospheric observations of the structure of, and activity in, the inner heliosphere from the two STEREO spacecrafts (launched 2006); in particular, imaging and tracking solar ejecta from the Sun to the Earth and other planets. This has expanded considerably our understanding of the propagation and development of mass ejecta in the heliosphere and their impacts on Earth.

On p105 the observations by Hinode of the solar poles means that the second paragraph should be updated to read: ‘High sensitivity exposures with the Hinode spectropolarimeter have shown us that the fields at the poles concentrate in kG structures, much in the same way as everywhere else on the Sun. However, the fast, small-scale, dynamics that produce the polarity reversals that seed the following magnetic cycle cannot be observed from within the ecliptic. It is basically unknown at which latitude the meridional flow stops and submerges

inside the Sun and if it carries any sizeable magnetic flux with it. This leaves the processes that seed with magnetic flux the upcoming solar cycle as a basically an unexplored issue.'

As with the point above, on p105 in the middle, the missing item here is the new field opened up using STEREO, which has demonstrated the ability to image and track solar mass ejecta using spacecraft stationed outside the Sun-Earth line. This has allowed the imaging of Coronal Mass Ejections (CME) and has provided complementary in-situ observations that has opened up an active world-wide study of CME propagation models and their application to space weather as well as to the physics of mass ejection processes. These are fundamental to the structure and evolution of a stellar atmosphere and to the impacts on our environment.

The last paragraph on p106 argues about the need of sophisticated inversion codes to make progress in our determination of solar abundances. While this is fully justified a reference to the phenomenal work that is being done with simulations should be added so that the interplay between observation-inversion and simulations is brought out. A suggested addition would be: 'These efforts must be complemented with ever more realistic MHD simulations of the dynamic, magnetic and thermal conditions in the solar atmosphere that can be used to calibrate the forward problem and validate the inversion algorithms. Recent progress with these simulations now cover from several million miles below the atmosphere to Chromospheric and Transition Region heights, including departures from the single fluid description offered by the MHD. These simulations are modeling structures such as granules and sunspots to an impressive level of detail, even if the required non-dimensional numbers parameter space is not realistically covered yet.'

5.2: What drives Solar variability on all scales?

Since the SV it has become clear that we experienced an extreme solar minimum of activity in the period 2008-2010, with sunspot and flare levels at a hundred year low for an extended period. This was not predicted and, despite the return to activity from 2010, heading to a maximum in 2012/13, the fact that we do not understand this low activity period has generated much interest and stressed that there is much still to learn about our star.

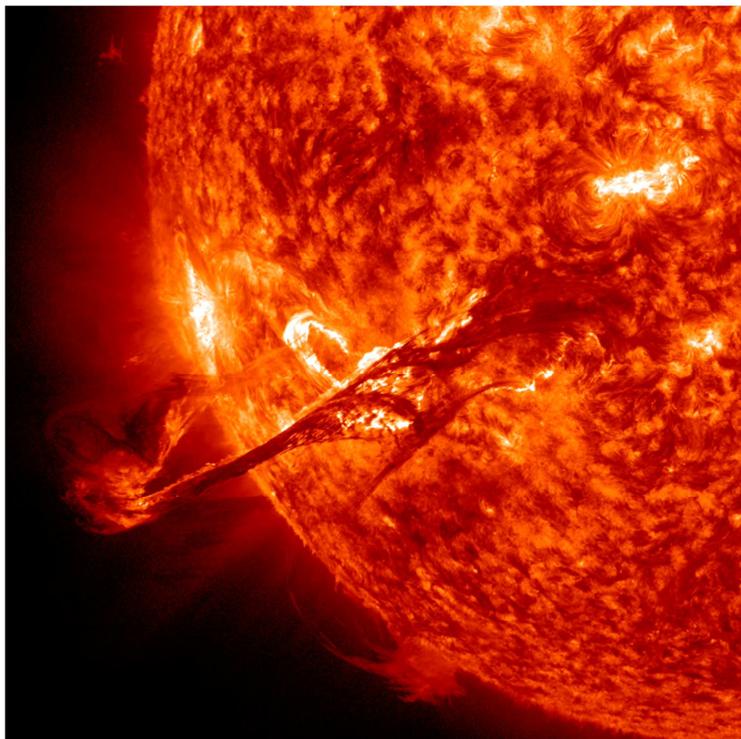
In section 5.2.2 on p109 in the second paragraph there should be some reflection on the progress made over these years in the spicules field (Type I/II debate). We can now say that much progress has been made observationally with the finding of swaying motions and torsional waves in the chromospheric structures known as spicules, indicating the presence of wave power propagating upwards.

There are still many questions regarding Solar magnetic fields: how much flux is present on the Sun, how is it distributed and how does the distribution vary on different time scales?, how does flux emerge and how is it removed? Answering such questions requires long-term synoptic observations with a ground-based network of medium-sized synoptic telescopes continuously observing and providing vector magnetograms with a resolution of better than 1 arcsec, and high cadence. This could be most adequately achieved by extending the existing SOLIS facility (NSO-led, USA) to a three-location network.

5.3: What is the impact of Solar activity on life on Earth?

In Section 5.3.1 the space weather background section covers most relevant areas already but, in the specified areas of the second paragraph, which highlights topics of particular interest, a statement about the importance of understanding the solar activity cycle – in light of the unexpected, extended recent solar minimum (see above) now needs to be inserted. Also, paragraph two should include particle acceleration associated with CME shocks.

In the following section 5.3.2 on p112 note should be included that much progress has been made in this area and the SV is now outdated by the science coming out of the STEREO mission with the identification and tracking of Earth-directed CMEs and the imaging of the

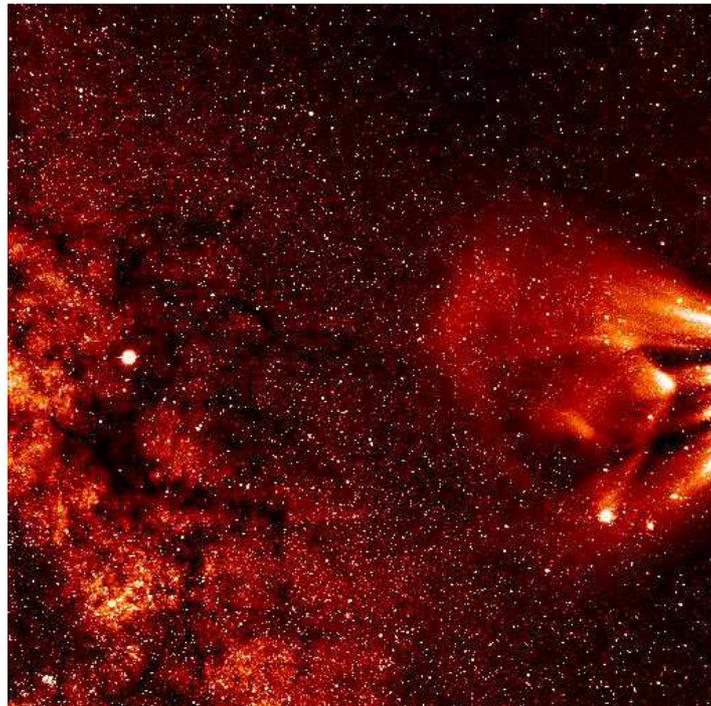


An erupting solar prominence imaged in the EUV from NASA's SDO spacecraft (courtesy SDO team)

whole Sun (see general comments earlier). While there is much research to be done and the fundamental questions posed remain the same, huge strides have been taken in developing the capabilities and developing the field.

The last paragraph talks about synoptic data and SDO. The SDO data are providing routine high-resolution imaging of the Sun from Earth orbit. A view of the complete Sun is being provided on a synoptic basis with SDO and STEREO, while a synoptic view of the inner heliosphere is being given by STEREO. In short, our synoptic mapping of the Sun/heliosphere has come a long way since SV and it provides a superb foundation for current research.

In the same section and page the second to last paragraph appears to advocate a truly polar mission that was probably written when such a mission was being pursued in various fronts (Cosmic Vision and Solar-C plan A). However, with the selection of plan B for Solar-C, it is clear now that this mission will not be proposed in any serious form for the next 5 years or so. If there is to be support for European participation in Solar-C then the following could be added: ‘The access from space to high sensitivity, spectrally resolved, polarimetric data from Hinode has proven highly valuable. Continuing this effort to provide similar observations with higher polarimetric sensitivity and better spatial resolutions would provide fundamental insights to understand how connectivity of the different layers of the solar atmosphere occurs. This is particularly relevant for the least explored layer of the Sun, the chromosphere, that is currently believed to hold the keys to our understanding of propagation of mass and energy to the upper layers and into the heliosphere’.



A solar coronal mass ejection seen passing through the heliosphere by one of the STEREO spacecraft (image is 20 degrees across with the Sun 4 degrees off the right hand side). Note the Milky Way and Jupiter to the left (courtesy STEREO/HI team).

5.4: What is the dynamical history of the Solar System?

Europe, in particular, has a long tradition of modelling the formation of the Solar System. In recent times such models have become guided by detailed chemical and isotopic measurements of meteoritic components. Such work has been used to document the extent of mixing within the nebula as a whole. At the same time, highly focussed isotopic investigations have uncovered remnant pre-solar grains, which in turn give an insight into the nature and distribution of materials present at the time of Solar System formation. By comparing isotopic measurements made in the laboratory with equivalent observations of

astronomical entities it has been possible to contemplate the extent and influence of broad-scale phenomena during the accretionary process. Models that implicate so-called x-winds, or involve components from AGB stars or Wolf-Rayet stars have been proposed; collapse initiated by a supernova shock-wave remains an active area of enquiry.

In this light, significant progress has been made since 2005 in the development of numerical simulations of the early history of the solar system, especially with the 'Nice Model' at Observatoire de la Côte d'Azur (OCA, France). This model strongly suggests that some migration of the giant planets has taken place in the early stages of their history, and we see traces of it, in particular, in the Late Heavy Bombardment and in the present structure of the Kuiper Belt. It is now generally accepted that a moderate migration drove Jupiter inward while the three other giant planets moved outward. When the Jupiter/Saturn system crossed the 2:1 resonance (where Saturn's revolution period is twice that of Jupiter's) at a time about 800 million years after the Sun and planets' formation, strong disturbances appeared in the orbits of small bodies, with, occasionally, very high values of their inclinations or eccentricities. The subsequent strong increase in the collision rate was probably responsible for the Late Heavy Bombardment that is observed from the surface cratering rates of most of the bare small bodies. Dynamical models also suggest that in an earlier phase, Jupiter might even have approached the orbit of Mars - thus explaining its relatively small size as compared with the other terrestrial planets - before being driven back outward under Saturn's influence.

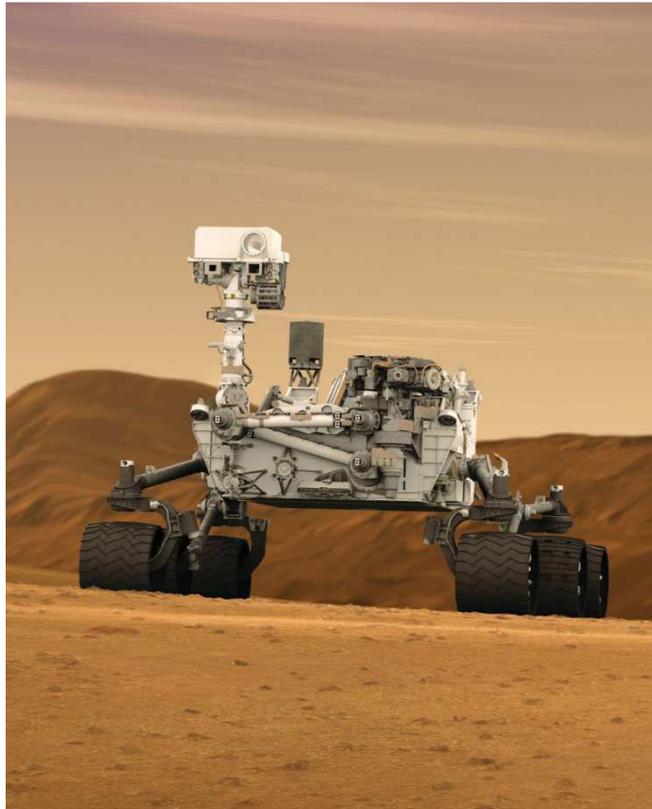
These results illustrate the strong link that now exists between dynamical models of the Solar System and dynamical simulations of extrasolar planetary systems, where migration is believed to be a relatively common process. In the case of the Solar System, the quasi-simultaneous formation of two big planets, Jupiter and Saturn, may have prevented Jupiter from coming too close to the Sun, in the way that many giant exoplanets are seen to approach their host star.

5.5: What can we learn from Solar System exploration?

The planetary exploration has known a significant evolution since 2005. Regarding Mercury, Messenger (launched in 2004) has mapped most of its surface; the next step will be BepiColombo (ESA, JAXA, with an expected launch in 2015) to explore Mercury with two spacecraft to undertake surface and plasma measurements. Venus Express (launched in 2005) is still operating in orbit around Venus for studying the composition and dynamics of its atmosphere.

The exploration of Mars has been a prime target of space studies thanks to several missions: ESA's Mars Express (launched in 2003), NASA's Mars Exploration Rovers of Spirit and Opportunity (launched in 2003), NASA's Mars Reconnaissance Orbiter (launched in 2005), the USA's Phoenix (launched in 2007) and finally the recent NASA Mars Science Laboratory with the Curiosity lander that has been in operation since mid-2012. Among many discoveries, these observations have led to a better understanding of the history of water of Mars. It is now generally agreed that water was very abundant in liquid form at the surface in the early stages of its history. The exploration of Mars will continue with MAVEN (NASA

small mission to be launched in 2014) to explore the loss of the Martian atmospheric and later with the ExoMars mission. This project, led by ESA and Russia, will include an orbiter and a descent lander and is planned for launch in 2016. A rover devoted to exobiology studies is to be launched two years later. The objective is to search for past or present signs of life by obtaining and analysing sub-surface samples extracted with a drill. In parallel, the NASA mission InSight, to be launched in 2016, will be devoted to the study of the internal structure of Mars, in particular by seismology.



The rover Curiosity, launched by NASA in November 2011, presently in operation at the surface of Mars since August 2012.((c)NASA)

The exploration of Saturn's system, in particular its moons Titan and Enceladus, is continuing with the Cassini orbiter. Important results include the discovery of hydrocarbon lakes on the surface of Titan that are subject to seasonal effects and the evidence from plumes outgassed from Enceladus that suggest the possible presence of liquid water below its surface. In 2016, the Jupiter system will be further explored with the arrival of NASA's Juno mission. Its main objectives are the measurement of its water content in the deep troposphere as a diagnostic of the planet's origin, and an in-depth study of its magnetosphere. Further in the future, the ambitious ESA JUICE mission, to be launched in 2022, has recently been selected for in-depth monitoring of Jupiter's atmosphere and magnetosphere, as well as its icy Galilean satellites. The mission will address, in particular, the question of their habitability (see below).

After the discovery of the first trans-Neptunian object (TNO) in 1992, the study of TNOs has been developing at a steady rate thanks to ground-based systematic surveys using, in particular, the VLT. Over 1400 TNOs are known today with at least one of them, Eris, having a size comparable to Pluto. Indeed, these results motivated the decision taken by IAU in 2006 to withdraw Pluto from the list of the ‘official’ planets and to recognize it as the first discovered TNO. Our knowledge of TNOs has also benefited from space observations by the Spitzer and Herschel spacecraft, which have measured their thermal emission, allowing the determination of both their size and albedo. The New Frontiers mission, launched in 2006, will approach Pluto in 2015 and probably a second TNO sometime later.

Finally, the study of comets remains a priority for planetology, as these primitive objects can bring important clues about the conditions of formation and early evolution of the Solar System. In addition to the two already-known reservoirs, the Oort cloud and the Kuiper Belt, a third reservoir has been proposed in the outer main asteroid belt. The Rosetta mission, launched by ESA in 2004, will approach comet Churyumov-Gerasimenko in 2014, when a descent module will be sent to its surface for an in-situ analysis of the physical and chemical properties of the nucleus. In particular, astronomers hope to learn about the possible presence of prebiotic molecules (see below).

5.6: Where should we look for life in the Solar System?

There are different niches where traces of life can be searched for in the Solar System. The first possible candidate for habitability is Mars, which, for exobiologists, remains a primary target for space exploration. Results from Mars Express and Mars Reconnaissance Orbiter strongly suggest that abundant amounts of liquid water have flown on the surface of Mars in its early history (see above). These missions, along with the Curiosity rover have also confirmed the presence of hydrated minerals such as clays and sulphates that also attest to a more water rich past. Indeed, the presence of hydrated clays on Mars and minerals such as jarosite, which suggest acidic conditions, reveal that the surface of Mars was heterogeneous and that the physical and chemical conditions for life and habitability in general may have varied markedly across the Martian surface. This changes the older paradigm that viewed Mars as having a rather homogenous surface and shows the potential complexity and diversity of environments that can be assessed as potential locations for life. All of this suggests that old terrains should be targeted for future in-situ observations and the site of the ExoMars rover landing will probably be chosen following these criteria.

Another niche is the interior of outer satellites of the giant planets, as models of internal structure of the icy outer satellites suggest that liquid water might be present. The case of Europa is of special interest because the liquid ocean might be in contact with the rocky surface, opening interesting implications for exobiology. The JUICE mission (see above), although primarily designed for the exploration of Ganymede, will make two flybys of Europa and bring new information on the nature of its surface. More generally, the JUICE mission will investigate the condition of habitability for outer icy satellites.

Other outer satellites may also contain liquid water: it could be the case for Enceladus where Cassini detected water plumes. Although we cannot be certain that Enceladus is a potential habitat for life, it is definitely the location for complex organic chemistry and may yield insights into the formation of prebiotic compounds. This is important as the search for life in the Solar System also includes that of prebiotic matter and the composition of the organic material in the Enceladus plumes is one of the key questions for the future.



Evidence for cryogenic volcanic activity has been found on Enceladus by several instruments of the Cassini orbiter, including the detection of outgassing plumes and the evidence for a higher temperature around the south pole. It has been suggested that Enceladus' outgassing is at the origin of the E-ring of Saturn. The evidence for cryovolcanism suggests that liquid water might be present inside Enceladus' interior. However, the source of heating on such a small satellite is not fully understood presently. ((c) NASA-Cassini)

Potential laboratories for prebiotic chemistry can be found in Titan and also in comets. The exploration of Titan by Cassini has revealed the presence of very complex hydrocarbon and nitrile species in Titan's ionosphere. For the first time, cometary samples have been analysed on Earth after the sample return from comet Wild 2 by the STARDUST mission, and the presence of glycine, a simple amino-acid, has been reported. In the future, the encounter of comet Churyumov-Gerasimenko by the Rosetta mission in 2014 (see above) should bring important new information for exobiology.

Chapter 6: Recommendations

In this section of the Update the *original* Science Vision recommendations are reproduced in two forms: firstly the ‘narrative’ – a general description of the key themes and requirements; secondly in the form of the left-hand column of the tables below. There are very few changes to the original narrative and these changes are indicated by **coloured script**. The original narrative is immediately followed by an ‘updated narrative’ section.

In the tables, the right-hand columns are the updates on the original suggestions. It should be noted that in the original document there was not always consensus on what constituted a future mission – sometimes an approved space mission was classed as ‘current’, however, the original recommendations have been retained intact so that the reader can readily understand what the *updates* refer to in the context of the Science Vision document.

6.1: Cross Disciplinary Requirements

There is no change in this section.

6.2: Do we understand the extremes of the Universe? (*from the original Science Vision*)

The questions posed in this section are a mixture of astrophysics and fundamental physics, and lie at the very foundation of our understanding of the Universe, its composition, and its formation. The specific science goals reflect this mixture:

1. Measure the evolution of the dark-energy density with cosmological epoch, to search for deviations from a cosmological constant;
2. Test for a consistent picture of dark matter and dark energy using independent and complementary probes, thus either verifying General Relativity or establishing the need for a replacement theory;
3. Measure the polarization of the cosmic microwave background **at scales of a few degrees**, to search for the signature of relic gravitational waves;
4. Directly detect astrophysically-generated gravitational waves to measure strong-gravity effects, in particular arising from black-hole coalescence;
5. Make direct studies of regions near the event horizon of supermassive black holes in galactic nuclei, to test strong gravity and to understand how large-scale relativistic jets are launched;
6. Understand the astrophysics of compact objects and their progenitors, particularly the functioning of the supernova explosion and gamma-ray burst mechanisms;
7. Understand the origin and acceleration mechanism of cosmic rays and neutrinos, especially at the highest energies.

These goals map into a clear set of facilities, although not always in a one-to-one manner. A number of attractive current and potential future facilities exist that are capable of addressing

several of the questions of prime interest, in whole or in part. This multiplicity is highly beneficial for independently crosschecking the reality of some of the more subtle phenomena at issue. Many of the current facilities will have long lifetimes in their existing forms, and have well-motivated plans for upgrades. Except where there is inevitably a fixed lifetime (e.g., a cryogenic satellite), or where a future facility is a clear replacement, it should be assumed that current facilities will continue to be required.

6.2.1: Narrative update - 2013

The consensus is that all the science questions in SV are still valid; dark energy is now an established field of in its own rite with numerous studies underway. However, perhaps an additional science goal on the particle-astrophysics boundary could now be injected. This is to seek to make a direct connection between cosmology and particle-physics data, emphasising the need for support of direct-detection dark matter experiments and how these are impacted by data from the LHC.

Current facilities (as defined in the Science Vision of 2007)

- Planck will be essential for goals 1 & 2 and complementary for goal 3 since cosmic microwave background (CMB) information underlies most of statistical cosmology. Planck will measure the unpolarized properties of the CMB effectively to the ultimate limits imposed by cosmic variance;
- Direct dark-matter detection experiments and indirect searches for dark matter via high energy gamma-rays are essential for goal 2, and have the potential to prove that it is a supersymmetric relic particle.
- SWIFT, XMM and INTEGRAL are providing essential data for goal 5 & 6, allowing us to address the study of neutron stars and black holes in binary systems and to clarify the progenitors and the physics behind GRBs;
- Ground-based gravitational wave detectors will be essential for goal 4. Low-mass black-hole mergers generate signals in the kHz bands that can be accessed from the ground. Existing detectors may lack the sensitivity for carrying out these astronomical measurements now, but are needed as a basis for more powerful facilities;
- The 8–10 m class optical telescopes (including the VLT, GTC, LBT and Gemini), as well as interferometers, like the VLTI are essential for goal 5. Astrometric studies of orbits near the centre of our Galaxy are the best evidence for a nearby massive black hole, and this case should strengthen with time and increased sensitivity due to upgrades of instruments;
- H.E.S.S. will be essential for goals 5 & 7 in order to study the production of very high energy gamma-rays;
- The Pierre Auger observatory will be essential for goal 7. To determine the origin of high-energy cosmic rays will require huge air shower arrays and air fluorescence detectors;
- LOFAR will be complementary for goal 7. Synchrotron radiation from cosmic-ray shower debris can help pin down the energy of the initial event.

Update includes approved missions/facilities as appropriate (2013)

- Polarization properties will be limited by removal of galactic foregrounds, but Planck has the best variety of frequencies for this purpose. *A major continuing effort will be required to understand the foreground signals in Planck data to the highest levels of precision*
- no change

- These missions continue to be crucial to achieve the goals

- Good progress has been made on ground-based GW detectors. The European Pulsar Timing Array is aimed at detecting a general background of gravitational waves from supermassive blackhole binaries.

- There is no longer a European share in Gemini, but there are partnerships with SALT and HET.

- HESS has been upgraded and is now joined by MAGIC and VERITAS

- Pierre Auger Observatory now operational and the northern site has been selected.

- LOFAR is now operating.

Future facilities (as defined in the Science Vision of 2007)

- The planned SKA will be essential for goals 1 & 2. A sufficiently sensitive radio telescope can obtain HI redshifts and image shapes for a large fraction of all galaxies out to redshift one, allowing gravitational lensing and large-scale structure studies of cosmological geometry. The main requirement is a large field-of-view, so that the whole sky can be imaged within a few years. Improved tests of General Relativity can also be expected from the large sample of new pulsars expected from such a facility, which will be complementary for goal 5;
- An X-ray survey satellite will be essential for goals 1, 2 & 6. Large-area X-ray imaging is important both for the detection of clusters of galaxies, and also for monitoring to detect transient explosive sources;
- A wide-field imaging telescope in orbit will be essential for goals 1 & 2. Combining photometric redshifts with sub-arcsecond resolution imaging enables the principal tests of dark energy: Gravitational lensing, baryon oscillations, cluster evolution, and new supernova samples. Ground-based colours should be allied with space precision imaging and near-IR photometry. Wide-field spectroscopy from the ground is also needed to calibrate the photometric redshifts;
- An Extremely Large Telescope (ELT) will be essential for goals 2 & 6. Fundamental cosmology will require spectroscopic classification and testing of systematics of supernovae at extreme redshifts, and also through hyperaccurate quasar spectroscopy, which can limit variation of the fundamental constants and measure directly the acceleration of the Universe. The understanding of thermonuclear and core-collapse supernovae and their connection to gamma-ray bursts, calls for detailed spectroscopic observations of the debris in the optical and infrared. At the highest redshifts, this will only be possible with an ELT. Both these applications require a mirror substantially enhanced from the current 8–10 m standard, to 30–40 m;
- The Cherenkov Telescope Array will be essential for goals 2 & 7. The physics potential is well defined by the impressive results from today's TeV gamma-ray telescopes. Detailed understanding will be gained of the acceleration of relativistic particles in supernova remnants and active galactic nuclei, and dark-matter annihilations may also be detected;

Future facilities update (2013)

- The SKA sites now selected, International Project office set up and the SKA Director is now in place. MeerKAT and ASKAP are now operational

Also the goal of the European Pulsar Timing Array

- While no current facility to achieve these goals is approved, eRosita will provide an imaging and spectral all-sky survey and the LOFT mission (ESA candidate M3 proposal) will provide some transient detection capability
- Euclid will provide in-orbit optical imaging plus near-IR imaging and spectroscopy.

This will have to go very deep and so will require 8-10m class telescope and IR spectroscopy

- The E-ELT is approved but not yet fully funded

- The CTA is now a well-defined project and full funding is anticipated soon.

- Plans need to be put in place for a follow-on mission to SWIFT to monitor and localise gamma-ray bursts.

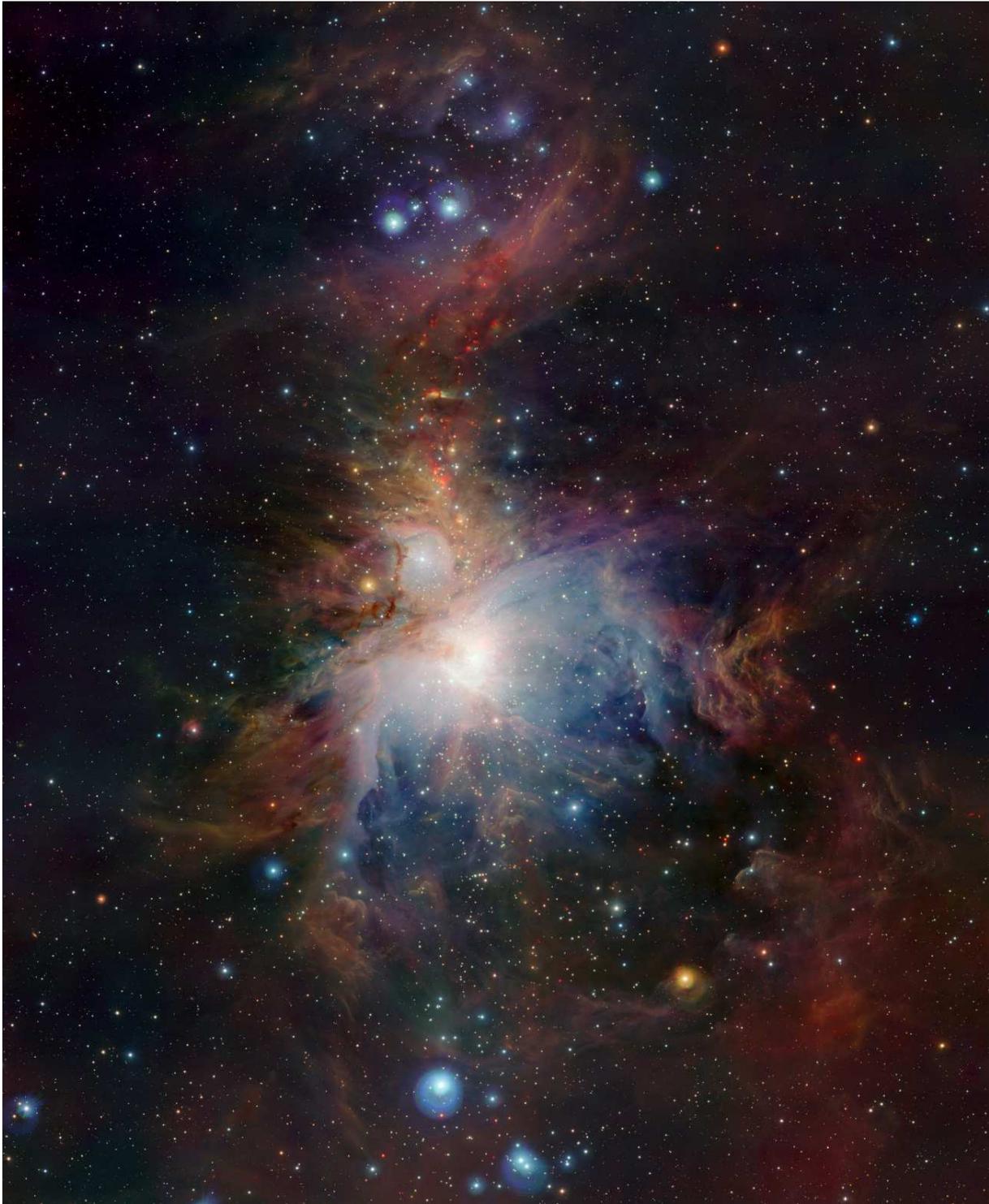
6.3: How do galaxies form and evolve? (*from the original Science Vision*)

The challenge of understanding galaxy formation and evolution is fundamentally intertwined with the challenge of understanding the structure and evolution of the Universe itself. To address these challenges the following important goals can be identified:

1. Map the growth of matter density fluctuations in the early Universe, both during and after the Dark Ages;
2. Detect the first stars, black holes, galaxies, **gamma-ray bursts** and supernovae, and thus establish the nature of the objects that reionized the Universe and discern the first seeds of galaxies; trace the **reionization history of the Universe through coordinated observations of the IGM (in absorption and emission), the highest redshift galaxies and quasars;**
3. Determine the evolution of the galaxy cluster mass function and constrain the equation of state of the dark energy;
4. Make an inventory of the metal content of the Universe over cosmic time, and connect its evolution to detailed models of star formation, and the subsequent metal production and ejection from galaxies by superwinds;
5. Measure the metallicity of the warm-hot phase of the intergalactic medium in the local Universe and its **contribution to the baryonic census;**
6. Measure the build up of gas, dust, stars, metals, magnetic fields, masses of galaxies and thus the evolution of the Hubble sequence with cosmic time and the connections between black hole and galaxy growth;
7. Obtain a comprehensive census of the orbits, ages, and compositions of stars in our own Galaxy and the nearest resolved galaxies, aiming to produce a complete history of their early formation and subsequent evolution. This work will draw on current facilities (including those under construction) but will require new facilities covering the wavelength range from the low frequency radio to the gamma-rays.

6.3.1: Narrative update - 2013

This topic is evolving very rapidly with more data from large surveys and follow-up using dedicated facilities. It is expected that this will continue with 8-10m optical/IR telescopes, HST and other space observatories, ALMA and other ground-based submillimetre surveys and eventually E-ELT. In a fully multi-wavelength approach using these facilities the possibility is tantalisingly close to fully document, phenomenologically connect and ultimately physically understand the links between gas accretion and accumulation in galaxies, star formation, galactic winds, metal enrichment, AGN activity and quenching of star formation.



A wide-field, infrared view of the Orion Nebula (Messier 42) taken with ESO's VISTA infrared survey telescope. The image was created from images taken through *Z*, *J* and *Ks* filters and covers a region of sky about one degree by 1.5 degrees. Image courtesy of ESO/J.Emerson/VISTA.

Current facilities (as defined in the Science Vision of 2007)

- LOFAR will be essential for goal 1, and complementary for goals 2 & 6. It will reveal the first phases of galaxy formation via the observation of high redshifted (luminous) radio galaxies;
- Planck will be essential for goal 1, and complementary for goal 3 by tracing the earliest density fluctuations via the Sunyaev-Zeldovich effect and the polarization of the CMB;
- JWST will be essential for goal 2, and will be complementary for goals 4 & 6. Its infrared capabilities will allow the study of the first ionizing objects, dust production and evolution over cosmic timescales, (early) star formation and many other distant objects;
- XMM–Newton remains essential for goal 3, and complementary for goal 6. The continuous availability of the X-ray space telescopes XMM–Newton and Chandra is crucial to study the hot intracluster medium and active galactic nuclei often in combination with observations in optical, radio and sub-millimetre domains;
- The 8–10 m class optical telescopes are essential for goals 4 & 6, and will be complementary for goal 3, as the instrument to study high-redshift quasars and gamma-ray bursts and the absorption lines in their light;
- ALMA will be essential for goal 6, and complementary for goals 1, 2, & 3. ALMA will provide important information on the reionization, the evolution of dust and molecules at high redshift, the earliest epochs of structure formation, dust-obscured star formation and nuclear activity;
- HST (after the next servicing mission) will be essential for goal 5, and will be complementary for goal 6, by giving invaluable information about baryons in the intergalactic medium and (until JWST is operational) about the star formation in distant galaxies;
- Gaia will be essential for goal 7 by measuring very accurate positions, distances and motions of a billion stars all with spectrophotometry providing in effect a stellar census of our Galaxy;
- Herschel will be complementary for goal 6, and will study molecules and dust at intermediate and high redshift.

Update – includes approved missions/facilities as appropriate

- LOFAR is now operating
- Planck operations completed and first public data release available soon
- JWST launch now scheduled for 2018
- Both currently funded for continuing operations delivery science that continues to be crucial
- Also now includes goal 7 (through GAIA-ESO public survey)
- ALMA is now operational and will be fully populated by 2014; can now include NOEMA (upgraded IRAM PdB)
- Last servicing mission completed and is now undertaking crucial programme of observations
- Gaia is now planned for launch end-2013
- Herschel has successfully completed its mission
- VISTA essential for goal 2 by providing detections of candidates for the highest redshift quasars and galaxies before JWST, and complementary for goals 3 and 6 from its wide-field deep infrared imaging surveys;
- VLT essential for goal 7 by providing complementary spectroscopy for samples of order 10^5 stars in the Galaxy to measure chemical abundances and kinematics and the GAIA-ESO public survey is underway
- eRosita will be essential for goal 3 and complementary for goals 1 and 6 by providing the first imaging all-sky survey in hard X-rays, and identify tens of thousands of distant galaxy clusters and millions of accreting black holes;
- Euclid (now ESA approved M2) will be essential for goal 1 in providing definitive constraints on the dark energy equation of state, and complementary for goal 6, by providing enormous inventories of precise imaging, spectra, and redshifts for distant galaxies and complementary for goal 6 & 7 for stars in our Galaxy.

Future facilities (as defined in the Science Vision of 2007)

- An ELT with adaptive optics and high-resolution imagers will be essential for goal 6, and complementary for goal 2. Spectrometers ($R \sim 5 \times 10^4$), and highly multiplexed (near) infrared spectrographs (including multiple integral-field instrumentation) will be essential for goal 1, and complementary for goals 2, 4 & 6. It will characterize the evolution of large-scale structures over cosmic time, decipher the internal physics of high-redshift galaxies, directly resolve stellar populations in the local supercluster, and provide a powerful complement to the revolutionary information that will come from JWST and Gaia;
- SKA with large surface area and long baselines will be essential for goal 1, and complementary for goals 3 & 4 (for which combined observations with an ELT are required) & 6. The large surface area and large frequency coverage will be essential for goal 6, and complementary for goals 1 & 2. This instrument will address problems ranging from cosmic reionization to the formation of galaxies, stars, black holes, and magnetic fields, and build on the foundation of sub-millimetre to centimetre work that will be opened up by ALMA and LOFAR;
- It will be essential to continue to have the capability to detect gamma-ray bursts, which provide a unique way of probing the early Universe. Follow-up observations are necessary for goals 2 & 4;
- An X-ray space mission with moderate-resolution spectroscopy ($R \sim 1000$) will be essential for goals 2 & 5, and complementary for goals 3 & 4. This mission should address key problems relating to the intergalactic medium, missing baryons, black hole evolution, and galaxy assembly;
- A 4–8 m ultraviolet space telescope will be essential for goal 4, and complementary for goals 2, 5 & 6. Such a facility could obtain high-resolution imaging and spectroscopy of galaxies and background quasars over thousands of sightlines in the Universe, and trace the evolution of intergalactic baryons and the exchange of matter and metals between galaxies and the intergalactic medium over cosmic time;
- A 4–8 m cooled infrared telescope for spectroscopy will be essential for goal 6. It will trace dust-obscured galaxy formation, star formation, and black hole formation and growth back to the reionization epoch;
- LISA will be complementary for goal 2 by providing unique information about the (first) mergers of black holes;
- A wide-field optical-infrared imaging telescope capable to measure weak gravitational distortion of faint objects, will be complementary for goals 3, 6 & 7, and should provide firm evidence of the earliest cosmic star formation and constrain dark matter and dark energy;
- A far-infrared space interferometer will be complementary for goals 3 & 6 in connection with ALMA. It would allow observations of H₂ molecules at high redshift (dust-obscured and shock-heated regions).

Update

- The E-ELT is approved but not yet fully funded

- SKA sites now selected, International Project office set up and SKA Director in place. MeerKAT and ASKAP are now operational

- It remains crucial to be able to detect and localise gamma-ray burst (currently SWIFT)
- There needs to be an X-ray mission to achieve these goals, currently none approved.

- This remains an important requirement and it should be addressed in the next Science Vision 'decadal'

- This remains an important goal and is in principle satisfied by SPICA, which awaits further mission clarification by JAXA
- The descoped LISA (NGO) not selected as first ESA Large mission
- These goals will be satisfied by EUCLID now approved by ESA as M2

- This remains an important requirement and it should be addressed in the next Science Vision 'decadal'

Future facilities (as defined in the Science Vision of 2007)

- A wide-field, highly-multiplexed, low and high resolution spectroscopic survey telescope will be complementary for goals 6 & 7, it will be necessary to disentangle the relations between masses, ages, morphologies, and environments in order to understand the formation of galaxies.

Update

- ASTRONET Panel (Kaufman) clarified the complementary nature of near-IR (8m) and optical (4m) surveys: ESO study for MOONs (near-IR/8m) & 4MOST (optical/4m) - decision spring 2013; plus WEAVE (4m-WHT). For goals 6 & 7 and complementary for goal 3.

6.4: What is the origin and evolution of stars and planets? *(from the original Science Vision)*

Understanding the formation and evolution of stars is at the very foundation of explaining the past evolution and present structure of our Galaxy and the Universe as a whole. Equally relevant is understanding the evolution of circumstellar discs leading to the formation of planetary systems, the search and study of exoplanetary systems, including possible life-hosting systems, as they are all milestones towards putting our Solar System in context and determining our place in the Universe. To address these challenges several important goals can be identified:

1. Determine the initial physical conditions of star formation, including the evolution of molecular clouds, and the subsequent development of structures in general, and the formation and mass distributions of single, binary or multiple stellar systems and stellar clusters;
2. Unveil the mysteries of stellar structure and evolution, also probing stellar interiors;
3. Understand the life cycle of matter from the interstellar medium to the processing in stars and back into the diffuse medium during the last stages of stellar evolution;
4. Determine the process of planet formation, aiming for a full understanding of the timeline for the formation of planets and the chemical evolution of the material that will eventually end up in exo-planets;
5. Explore the diversity of exo-planets in a wide mass range from giants to Earth-like, to characterise the population of planetary systems in relation with the characteristics of their host stars;
6. Determine the frequency of Earth-like planets in habitable zones and push towards their direct imaging with the long-term goal of spectroscopic characterization including the detection of biomarkers in their atmospheres.

This ambitious programme requires substantial technological development in the coming decades. The techniques to be developed include coronagraphy, extreme adaptive optics, high-contrast imaging systems, extremely large telescopes, optical/infrared interferometry on the ground and in space, very large effective area and angular resolution millimetre and radio interferometers, transits, microlensing, radial velocity and astrometric planet searches.

6.4.1: Narrative update - 2013

This section remains mostly unchanged but over the past 5 years there has been a tremendous development of the exploration of exoplanets by transit, thanks to CoRoT, Kepler and ground-based surveys. The characterization of exoplanets' atmospheres by transit spectroscopy will be the next step of the roadmap. The ESA S1 CHEOPS mission will search for bright targets for future spectroscopic studies. The more ambitious PLATO mission (M3 candidate) has a similar objective. EChO, another M3 candidate, is aiming at the spectroscopic characterization of transiting exoplanets. A major input is expected from Gaia in the systematic detection of nearby exoplanets, and space missions dedicated to the systematic study of exoplanets are now mature and are essential to progress in the characterization of the physical properties of planets (see later for details).

The impressive results from the Herschel Space Observatory and the expectations from future spectroscopic far infrared mission suggest that from the ground most of the progress in the submillimetre through radio bands in the future will come from high angular resolution and high sensitivity instruments like ALMA, JVLA and, on a longer timescale, the SKA. The role of single dish telescopes, even of relatively large aperture, will decrease. High resolution optical and infrared spectroscopy is reaffirmed as a key role for the study of the interstellar medium, stellar evolution and exoplanets.

Current facilities (as defined in the Science Vision of 2007)

- The 8–10 m class optical telescopes are essential for goals 1, 2, 3 & 5, and complementary for goals 4 & 6, and need to be fully exploited and upgraded;
- The HST and current generation of X-ray space observatories are essential for goals 1 and 2, and complementary for goals 3 & 4. It will be an asset to keep these facilities at least until a next generation of facilities will become available. Alone and in combination with simultaneous observations in the optical, radio and sub-millimetre domain, they provide important information of all phases of stellar evolution and activity;
- Herschel and JWST will be essential for goals 1, 3 & 4, and will be complementary for goals 2 & 5. High angular resolution and sensitivity in the near- to far-infrared, as provided by space missions provide essential data not accessible from the ground;
- ALMA and its future upgrades will be essential for goals 1, 3 & 4, and will be complementary for goals 2 & 5. High angular resolution and high sensitivity millimetre continuum and line spectroscopy will be key to understand the physical and chemical evolution of dust and gas in the early phases of planet formation;
- Large millimetre single dish telescopes equipped with focal plane arrays for line and continuum observations are essential for goals 1 & 3, and complementary for goal 5, because of their ability to rapidly survey large areas of the sky and find sources for detailed studies of star- and disc formation and evolution with ALMA and the proposed SKA;
- Gaia will be essential for goals 2 & 5, and complementary for goals 1 & 6. Higher accuracy astrometric measurements from ground and space will extend the detection capability and resolve the degeneracy in mass and orbital inclination, quantify the relative orbital inclination of multiple exoplanetary systems and address fundamental topics in stellar structure and stellar populations in the Galaxy.

Update – includes approved missions/facilities as appropriate

- Maintaining and upgrading essential
- No change

- Herschel has successfully completed its mission; JWST launch planned for 2018. Important to fully support Herschel data exploitation and follow-up with high angular resolution submm Interferometry (ALMA)
- ALMA is now operational and will be fully populated by 2014 and it is essential to exploit ALMA fully within Europe, along with its planned upgrades

- Herschel has provided a wealth of data here that needs further exploitation with large ground-based single dish survey-type facilities providing much better angular resolution – current submm facilities now under threat

- Future development of this topic post-GAIA is now timely.

Future facilities (as defined in the Science Vision of 2007)

- Near- and mid-infrared imaging and spectroscopy at high spatial resolution and sensitivity provided by an Extremely Large Telescope with high performance adaptive optics will be essential for goals 1, 2, 3, 4, 5 & 6;
- A next generation of ultraviolet and X-ray missions will be essential for goals 1, 2 & 3, and be complementary for goals 4 & 5. They will provide higher sensitivity, spectral and spatial resolution to study the gas and dust around stars;
- SKA with long baselines and full frequency coverage will be essential for goals 1, 3, & 4, and complementary for goals 2 & 6. It will allow to resolve individual obscured cores of molecular clouds, trace the largest molecules and image the magnetic fields;
- The availability of both high-contrast and high-resolution sensitive infrared interferometer in space will be essential in order to answer goals 1, 4 & 6, and they will be complementary for goals 2, 3 & 5;
- High-precision photometry (better than 0.01 millimag) and long-term monitoring from space in conjunction with a ground-based dedicated network of moderate aperture (2m) robotic telescopes will be essential for goals 2, 5 & 6, and complementary for goal 3;
- The provision of high spectral resolution in the near-to-far infrared has to be included in planning for a fully adaptive ELT or interferometry from space, as the next step in the study of gas dynamics, solid state chemistry and molecular hydrogen and organic content in the planet-forming zones of discs and in the characterization of exo-planetary atmospheres over a range of important spectral lines: This capability will be essential for goals 3 & 6, and will be complementary for goals 1 & 4;
- The next generation of high precision radial velocity monitoring instruments will be essential for goals 5 & 6, and complementary for goal 3; with a velocity resolution better than 0.1 m/sec it allows the detection of earth like planets in habitable zones around solar type stars.

Update

- The planned instrument suite for the E-ELT will achieve most of these requirements– e.g. METIS and HIRES.
- Following the success of Plank and Herschel there is now an opportunity to refine the requirements in this field.
- The SKA Phase 3 will satisfy this requirement but should be addressed in the next Science Vision ‘decadal’
- This should be addressed in the next Science Vision ‘decadal’

- The candidate ESA M3 mission Plato will satisfy this goal, in combination with high resolution and high precision spectrographs from the ground.
- The planned instrument suite for the E-ELT will achieve most of these requirements – e.g. METIS and HIRES.

- This remains an important goal and following from the major successes in this area, now is an appropriate time to reformulate this goals with specific requirements

- High accuracy and stability infrared spectroscopy from space is an essential step to achieve the accuracy and sensitivity needed for the spectroscopic characterization of exoplanets and achieve goals 5 and 6 – the EChO candidate ESA M3 mission would be the first steps along the road.

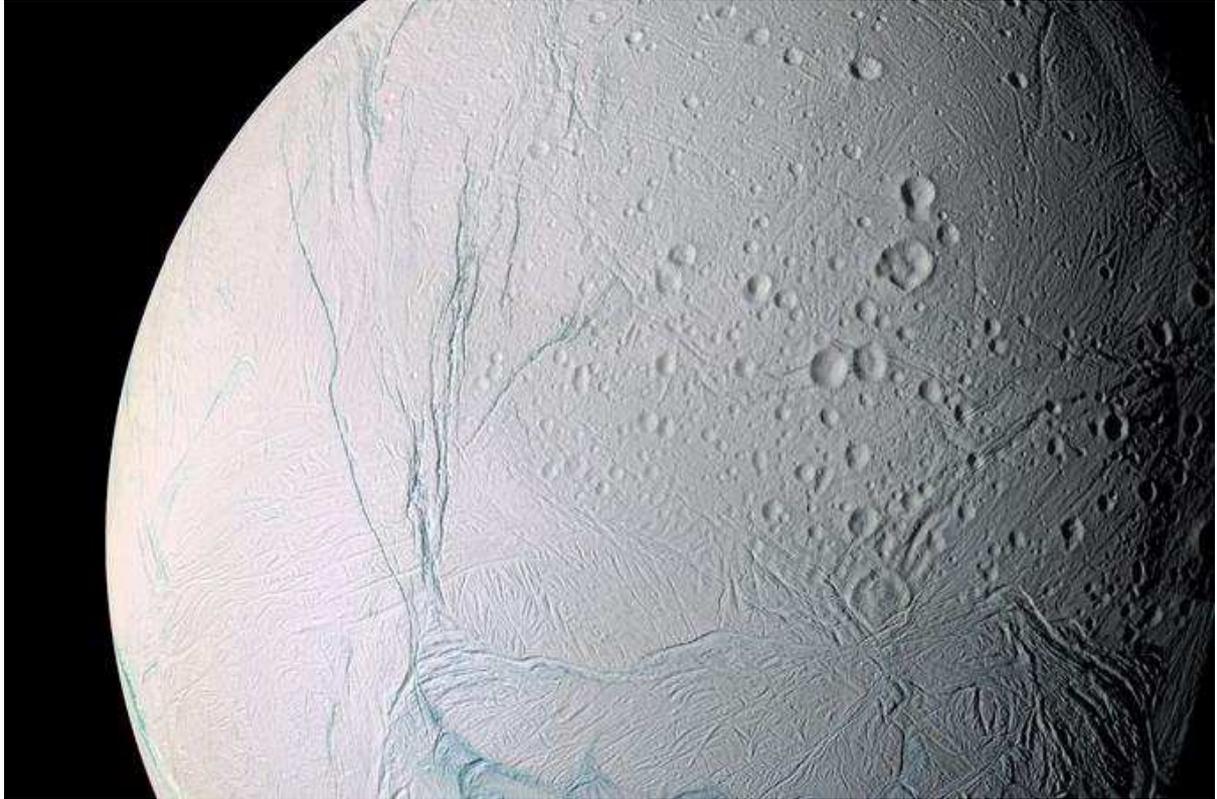
6.5 How do we fit in? (from the original Science Vision)

The Solar System is uniquely accessible to in situ and detailed remote sensing measurements. To better understand the formation, evolution, and detailed properties of the Solar System, and to understand its impacts on human activities, the following goals have been identified:

1. Utilise the vicinity of Solar System plasmas, in (i) the Sun, (ii) the heliosphere and (iii) planetary environments, to develop a detailed understanding of physical processes which apply to astrophysical phenomena;
2. Develop a unified picture of the Sun and the heliosphere including the planetary environments, including a systems-level view of energy flow from the Sun to the Earth;
3. Understand the underlying mechanisms for Solar variability and transient activity, the subsequent variability in the heliosphere and the resulting impacts on the Earth and other planetary environments;
4. Understand the role of turbulence and magnetic fields in the evolution of the primordial nebula, the mechanism of particle growth, and the elemental and isotopic ratios in this nebula, and in Solar System bodies;
5. Determine the dynamical history of planets, the composition of trans-Neptunian objects and asteroids, and the rate of large potential impactors in the near- Earth asteroid population; search for complex molecules in comets and study the link between comets and interstellar matter;
6. Constrain the models of internal structure of planets and satellites and the origin of their internal heat, the surface-atmosphere interactions and the recycling mechanisms in the terrestrial planets and outer satellites;
7. Understand the origin and evolution of Titan's atmosphere, searches for liquid water at the surface and subsurface of Mars, and for liquid water oceans below the surface of Europa and other outer satellites. Solar System research requires a wide range of complementing facilities which cover the full electromagnetic spectrum and probe a variety of space environments and planetary surfaces. These facilities are combined into groups of similar characteristics in this list.

6.5.1 Narrative update – 2013

Looking to the future, our dependence on the Sun is driving a marriage between science and applications as never before; in particular, with the new global views of our star and the imaging of solar ejecta in the heliosphere. These capabilities will undoubtedly be adopted for space weather and environmental monitoring in future years, with a programme of applications instrumentation running in parallel with advanced research projects such as Solar Orbiter. Whereas the solar science will focus on the new generation of solar encounters and high latitude science projects, the applications side will take the newly acquired skills from the current missions for heliospheric and solar 'surface' monitoring.



Cassini image of Saturn's moon Enceladus showing the icy surface pockmarked with craters and deep canyons. Image courtesy of ESA.

Current facilities (as defined in the Science Vision of 2007)

- The space solar observatories SOHO, STEREO, Hinode, ACE, Cluster, SDO and Ulysses are essential for goals 1–3 until next-generation Solar imaging and spectroscopy and in situ missions are available;
- Ground-based metre-class solar telescopes such as THEMIS, SST and GREGOR remain essential for goal 1(i) and complementary for goals 2-3, until a large aperture solar telescope becomes operational;
- Genesis and Rosetta provide measurements of comets and minor bodies in the Solar System, essential for goals 4 & 5;
- ALMA and LOFAR will provide the capability to do solar observations with a spatial resolution comparable to optical facilities, and will be complementary for goals 1& 2. Similar high resolution observations of planets, comets and trans-Neptunian objects are essential for goal 5;
- Mars Express, Mars Odyssey, Mars Reconnaissance Orbiter, Mars Exploration Rovers, ExoMars, Venus Express, Cassini, and Bepi-Colombo provide in situ measurements of planets which are essential for goals 6 & 7;
- Monitoring of many stars with high-resolution multi-object spectrographs at 4–8m class telescopes is complementary for goal 1.

Update includes approved missions/facilities as appropriate

- Ulysses is now deceased but Solar Orbiter is now accepted as ESA M1 for launch in 2017 and will satisfy goals 1-3. Solar Probe is in preparation by NASA.
- THEMIS and SST are fully operational while GREGOR is now being commissioned after first light in 2012..
- No change, NASA's DAWN mission has now mapped VESTA and will encounter Ceres in 2015
- Solar observations now beginning with LOFAR.
Specifically need high resolution, ground-based observations in the optical, near-IR and radio.
- This should include Mars Science Laboratory/Curiosity rover now in operation since August 2012. As a preparatory phase ExoMars is planned for launch 2016 (orbiter/descent module) and a lander/rover in 2018. ESA's BepiColumbo is now planned to launch in 2015 and to orbit Mercury in 2022.
- Need high resolution optical/infrared and radio – e.g. MOONs, 4MOST, WEAVE for example, ALMA is now operational

Future facilities (as defined in the Science Vision of 2007)

- A solar high-latitude, multiple Solar-encounter mission, climbing to at least 30 degrees out of the ecliptic and approaching to within 0.25 AU of the Sun, including a combination of high-resolution imaging and spectroscopy and in situ instruments is essential for goals 1(i), 1(ii), 2 and 3. It will establish the links between the Sun and its heliosphere as well as the polar regions of the Sun and the three dimensional nature of a star;
- Radio spectral imaging at centimetre to metre wavelengths, is essential for measuring magnetic fields in the corona, to identify sites of particle acceleration and to track travelling disturbances through the corona (goals 1(i), 1(ii) and 2);
- A large-aperture (3–5 m) ground-based solar telescope with adaptive optics and integral-field spectro-polarimeters, with a precision of one part in 10^4 , to resolve scales of order 10 km in the photosphere, to observe astrophysical processes at their intrinsic scales, and thereby observe the interaction of magnetic fields and plasma motions in the Solar atmosphere, is essential for goal 1(i) and complementary for goals 2 & 3;
- A medium-aperture (1–2 m) (extreme-)ultraviolet satellite facility with Xray capabilities, incorporating sub-arcsecond resolution imaging and spectroscopy, cadences down to seconds and wavelength selections appropriate to the temperature range of the Solar atmosphere – up to relativistic electrons – including, for the first time, (extreme-)ultraviolet magnetic mapping of the Solar transition region and corona, to study fundamental Solar processes that cannot be studied from the ground, is essential for goal 1(i) and complementary for goals 2 and 3;
- An in situ mission probing simultaneously the three major scales of the physical processes in the magnetosphere and Solar wind involving a fleet of spacecraft forming three embedded tetrahedrons. Essential for goals 1(ii), 1(iii) and 2;
- A high quality network of ground-based radars, such as SuperDARN and the next-generation EISCAT facility, providing both global context for the magnetospheric missions and specific detailed measurements in support of conjugate studies. Essential for goal 1(iii) and 2;
- A combination of magnetically conjugate ground-based and space-borne instrumentation to investigate the interchange of plasma populations in the Earth's magnetic environment is essential for goal 3;
- Future exploration of minor bodies in the Solar System, in particular near-Earth asteroids, is essential for goal 4 & 5;

Update

- Solar Orbiter will achieve these goals and is now approved as the ESA M1 mission for launch in 2017

- LOFAR and cm radio telescopes will achieve these goals

- The planned European Solar Telescope (EST) will meet these requirements and has completed the conceptual definition phase; there is European (German) involvement in the similar US ATST that is under construction in Hawaii.

- The Japanese Solar-C (1.5m) mission meets most of these requirements and ESA sees this as a 'Target of opportunity'. The European involvement would focus on UV spectroscopy and the mission also includes X-ray imaging.

- The science remains important but there is no European mission to achieve this; in the USA, MMS is under development by NASA for a launch in 2014.

- Planned upgrade to EISCAT-3D is on the ESFRIT Roadmap,

- No change

- The NASA New Horizons Mission will approach the Pluto-Charon system in 2015 and probably later other trans-Neptunian bodies; also now the ESA candidate M3 mission MARCO-POLO

Future facilities (as defined in the Science Vision of 2007)

- Space missions to the outer Solar System to explore the Jovian system, in particular Europa, and the Saturnian system, in particular Titan and Enceladus are essential for goals 6 & 7;
- A Mars sample return mission as follow-up to recent orbiter, lander and rover missions, coupled with laboratory infrastructure for sample analysis, is essential for goals 6 & 7. Future exploration of other terrestrial planets is also essential for goal 6;
- JWST and an ELT will allow imaging spectroscopy of planetary atmospheres and surfaces, comets, and trans-Neptunian objects and are essential for goals 6 & 7;
- Participation in an international network of ground-based, synoptic instruments that monitor continuously the full-disc Solar spectral irradiance and magnetic and velocity fields is complementary for goals 1(i), 2 & 3

Update

- The JUNO mission will reach Jupiter in 2016, and the ESA-approved JUICE mission is planned for launch in 2022, arriving at the Jupiter system around 2030
- As a preparatory phase ExoMars is planned for launch 2016 (orbiter/descent module) and a lander/rover in 2018. ESA's BepiColumbo is planned to launch in 2015 and to orbit Mercury in 2022 (see above). Sample return is in the realm of the next Science Vision 'decadal'
- JWST planned for launch 2018, E-ELT approved but not yet fully funded
- The ground-based network that fulfils this goal is the National Solar Observatory SOLIS network (USA)

Appendix 1 Science Vision Update Contributors

Panel A: John Peacock, Claes Fransson

Panel B: Jacqueline Bergeron, Rob Kennicutt

Panel C: Leonardo Testi

Panel D: Therese Encrenaz, Richard Harrison, Valentin Martinez Pillet, Ian Wright,
Charles Cockell

Members at Large and others: Catherine Turon, Alvio Renzini, Bruno Leibundgut