

EUROPEAN SPACE AGENCY

ASTRONOMY WORKING GROUP (AWG)

AWG recommendation on Cosmic Vision 2015-2025

At its 120th meeting held on 27-28 September 2004 at ESTEC, Noordwijk (NL), the Astronomy Working Group (AWG) thoroughly discussed the major astronomy themes for Cosmic Vision 2015–2025. These discussions followed the initial analysis of the answers to ESA's Cosmic Vision 2015-2025 Call for Themes which took place at the 119th AWG meeting and the inputs of the community during the ESA Science Workshop on 15-16 September 2004, in Paris.

Introduction

In answer to the Call for Themes, 47 responses dealing with astronomy topics were received, greatly exceeding the corresponding numbers from previous calls (Horizon 2000; Horizon 2000+). The AWG was overwhelmed by the quality and the quantity of the strong community response. This provides unambiguous evidence for the fact that astronomy is currently undergoing an era of great discoveries. The responses cover a large range of scales, from the physics of nearby stars and exo-planetary systems to the Universe as a whole, as well as all wavelength regimes of the electromagnetic spectrum.

The recommendations below have been the result of a positive selection process, through isolating those breathtaking topics the AWG considers absolutely mandatory to pursue for European Space Science, well aware of the fact it was not possible to include all strong and original ideas in the three major Themes. The AWG sincerely hopes that at least some of these issues can be revisited in the future as opportunities arise.

Relating the received proposals to the current and near-future instrumental development in astronomy, with particular regards to the ESA missions HST, XMM-Newton, Integral, Herschel, Planck, GAIA and JWST, as well as to the great scientific breakthroughs witnessed in recent times and expected to be achieved by ongoing and planned missions over the next decade, the AWG has identified three major scientific Themes which are believed to be at the forefront of astrophysical interest and research for the period considered, and for which space missions are mandatory to achieve huge steps forward for their understanding.

Theme 1: Other worlds and life in the Universe: placing the Solar System into context

This theme attempts to answer the ultimate question of human existence, namely whether we are alone in the Universe. After the striking discovery of an extra-solar planet in 1995, we have started to complete the Copernican Revolution. We live in the unique epoch where the question of the possible existence of other terrestrial planets in the habitable zones of stars can be addressed systematically for the first time. The European astronomy community is particularly strong in this field, building on the synergy between ground-based and space projects and dedicated theoretical studies.

In recognizing the overwhelming support for this theme, expressed also by representatives of the Solar System community, and drawing very strong public interest, the AWG has developed the following visions.

1.1 From exo-planets to biomarkers

After the first discovery of an extra-solar planet in 1995, there has been steady progress towards detecting planets with ever smaller masses, and towards the development of a broader suite of techniques to characterize their properties. There is no doubt that this trend will continue into the next two decades, as substantial technological challenges are progressively overcome. After Corot will have opened the way to telluric planet finding, the Eddington mission would get a first census of the frequency of Earth-like planets. GAIA will deliver important insights into the frequency of giant planets; the existence and location of such planets is crucial for the possible existence of Earth-like planets in the habitable zone. GAIA will also further improve our understanding of the stellar and Galactic constraints on planet formation and existence.

The next major break-through in exo-planetary science will be the detection and detailed characterization of Earth-like planets in habitable zones. The prime goals would be to detect light from Earth-like planets and to perform low-resolution spectroscopy of their atmospheres in order to characterize their physical and chemical properties. The target sample would include about 200 stars in the Solar neighbourhood. Follow-up spectroscopy covering the molecular bands of CO₂, H₂O, O₃, and CH₄ will deepen our understanding of Earth-like planets in general, and may lead to the identification of unique biomarkers. The search for life on other planets will enable us to place life as it exists today on Earth in the context of planetary and biological evolution and survival. Being aware of the technical challenge to overcome the high brightness ratio between star and planet and the advancements in technology reached during the past few years by ESA studies, **the AWG strongly and unanimously recommends the implementation of a mission addressing these objectives through a nulling interferometer for the wavelength range between 6 and 20 micrometers. Such a mission should be implemented around 2015, making Europe highly competitive in the field.**

The next step in this well-defined roadmap would be a complete census of all terrestrial extra-solar planets within 100 pc, for example through the use of high-precision astrometry. Longer-term goals will include the direct detection and high-resolution spectroscopy of these planets with large telescopes in IR, optical and UV wavelengths and finally the spatially resolved imaging of exo-Earths, leading to the new field of comparative exo-planetology.

1.2 From gas and dust to stars and planets

The formation of planetary systems has to be understood in the wider context of the process of star formation and the evolution of proto-planetary disks. We presently lack a generally accepted scenario for the formation of solar-type stars, with magnetic fields and turbulence being discussed as possible key factors in the birth process. We also had to realize that the newly detected “planetary worlds” are quite different from our own Solar System. These new findings cast doubt on existing theories of the formation of planets and planetary systems which have been based almost entirely on the singular case of the Solar System. The insight gained from observations of extra-solar planets has demonstrated the importance of planet-disk and planet-planet interactions, leading to such surprising results as the inward migration of giant planets and the question how stable such systems actually are. The problem is essentially one of nature versus nurture: is the structure of planetary systems a function of initial conditions provided by

the star formation process, or of interactions during its early evolution?

The understanding of the star and planet formation process requires a multi-wavelength approach, mostly from near-infrared to millimetre wavelengths. With the ISO mission, the upcoming Herschel observatory, the strong participation in JWST, and with the ground-based facilities of ESO and the ALMA project, the European star formation community is in a very strong scientific position. In order to make further progress in the field, and to complement the capabilities of ALMA, a far-IR mission is required. ALMA will not be able to access the important water lines, a key goal of a far-infrared mission. In addition, the peak of the spectral energy distribution is located at far-infrared wavelengths. Such a mission would need to provide spatial resolution of the order of 0.01 arcsec to resolve protostars and disks in the nearest star-forming regions, and should be able to perform high- and low-resolution spectroscopy to characterize line emission and dust mineralogy. **The AWG therefore supports a study of a far-infrared mission, to be launched in the timeframe after 2020.**

Theme 2: The early Universe

This theme is motivated by the recent establishment of a “standard”, concordant, cosmological model, and addresses fundamental questions like the origin of inflation, the nature of dark energy, and the history of creation of structures and objects throughout the visible Universe. Within this theme, there are currently two major visions driving the scientific endeavour.

2.1 Probing the fundamental nature of the Universe

The steadily growing successful synergy between cosmology and particle physics has led to the formulation of two key questions that are of fundamental importance for both fields.

2.1.1 Dark Energy

The totally unexpected discovery of a presently accelerating Universe leaves us with the quest for the driving force behind it. Termed “Dark Energy”, this component of the Universe currently has no explanation in terms of a physical model and is presently the largest challenge for fundamental physics. Unravelling the nature of Dark Energy will most likely lead to uncovering new and deep laws of physics. The two best means of investigating Dark Energy as currently identified are the weak lensing effect caused by the large-scale matter distribution in the Universe and the study of the luminosity-redshift relation of Supernovae Ia up to high redshifts. Precision measurements of both of these effects require a space-based wide-field optical and near-IR imaging capability.

2.1.2 Inflation

At its origin, our Universe is believed to have undergone a phase of rapid acceleration, called inflation. Generic predictions of inflation, such as the spatial flatness and the shape of the initial density fluctuations, have impressively been confirmed with recent observations, most noticeably the WMAP results. However, the physical mechanism driving inflation is unclear at present and competing physical theories exist. Since they differ in their predictions about the amplitude and shape of the primordial gravitational wave spectrum, determining those provides the key for deciphering the very beginning of the cosmos. The AWG is convinced that observing the polarization properties of the cosmic microwave background is the best approach for characterizing these primordial gravity waves within the envisioned time frame. It requires a multi-frequency all-sky map of the CMB polarization

with much larger sensitivity than Planck will achieve, which, due to the weakness of the signal, makes space-based observations mandatory.

2.1.3 Implementation

The AWG believes that these scientific issues will remain at the centre of cosmological interest for at least the next two decades and that great progress towards their solution can be achieved within the Cosmic Vision programme. To maintain Europe's leading role in wide-field imaging, and correspondingly, in weak lensing research, the optical/near-IR WFI should be implemented as soon as technically feasible. Experience from Planck will greatly benefit Europe's development of a CMB polarization mapper.

Therefore, the AWG unanimously recommends that an optical/near-IR wide field imager and an all-sky CMB polarization mapper should be studied..

2.2 Observing the Universe taking shape

The other aspect of this theme concerns astrophysical cosmology. The goal is to map the cosmic history back to the time when the first luminous sources ignited, ending the dark ages of the Universe by reionizing most of its atoms, after which galaxies and their supermassive black holes formed (see also theme 3). Merging of galaxies, their evolving large-scale distribution, their star-formation history, their relation to quasars, and their interaction with the intergalactic medium are processes that we have started to analyse, with HST, XMM-Newton and other telescopes, back to a time when the Universe had only about 10 % of its current age. Pushing this back to earlier times will be one of the great achievements of JWST. But even with JWST and other facilities foreseen in the next decade, several key issues will be left unanswered.

Noting that observational cosmology necessitates a multi-wavelength approach, no single observatory holds the key for completing the cosmic picture. The rapid evolution of this research area requires the flexibility provided by observatory-type missions, taking into account the current status and the prospects within the next decade, with observatories such as Herschel, JWST, and ALMA.

The first priority is a new generation X-ray observatory that should be able to observe clusters of galaxies back to their formation epoch, as witnesses of large-scale structure formation, the heating of the intracluster gas, its relation to the evolution of the cluster galaxy population, the impact of AGN activity on the intracluster medium, and its chemical enrichment; to detect the missing half of the baryons in the local Universe, most likely hidden in the warm-hot intergalactic medium (WHIM), through soft X-ray spectroscopy; to find the earliest indications of AGN activity, characterize its relation to star formation and galactic assembly, and locate the mergers of supermassive black holes expected to be detected by LISA. Therefore, **the AWG strongly and unanimously recommends the development of an X-ray observatory with a fast-track development to ensure its operation to at least partially overlap with the operation of LISA.**

In addition, a new generation far-IR observatory would be needed to resolve the far-IR extragalactic background light into discrete sources and locate the 50 % of the star-formation activity in the Universe hidden by dust absorption; to resolve star-formation regions in nearby isolated and interacting galaxies, to spectroscopically identify the cooling of molecular clouds with primordial chemical composition. These goals require the far-IR observatory to have an angular resolution of about 1.5 arcsec at a wavelength of 200 microns. To prepare for the implementation of such a capability, **the AWG recommends that ESA carry out a**

comparative study of a single dish versus an interferometer concept and, in addition, trade-off studies of either concept.

Theme 3: The evolving violent Universe

This theme is motivated by the recent results from XMM-Newton, Chandra and Integral, especially on the accretion and ejection mechanisms taking place in black holes and neutron stars, and the crucial interplay between black holes and galaxy evolution. It aims at probing deep inside the gravitational well of black holes and neutron stars, providing for the first time a thorough test of general relativity in the strong field limit, and deals with the physics of strong interactions in ultradense environments, the virulent processes in hypernova explosions leading to Gamma Ray Bursts, and binary black hole mergers.

3.1 Matter under extreme conditions

Astrophysics allows us to probe physics under much more extreme conditions than are possible on Earth. Black holes represent the triumph of gravity, so they are the ultimate objects for studies of General Relativity in the strong field limit. Neutron stars are only slightly less extreme in terms of gravity, but with the crucial difference that they have a surface rather than an event horizon, so that their internal structure has observable consequences. Where these objects accrete, they generically produce high energy emission which arises from deep in the gravitational potential well. Both the spectral and variability properties of this emission carry the imprint of the space-time curvature, allowing us to simultaneously test General Relativity and models of accretion, while for the neutron stars the strength of the gravitational field at the surface also discriminates between different models of the strong interaction for high density material.

These have been long-standing goals in the AWG science area, and are being addressed by ESA's XMM-Newton mission as well as by the US (RXTE and Chandra) and Japan (ASCA and ASTRO-E2). The response to the cosmic vision exercise was that the community unanimously confirmed the results of previous studies which identified a large X-ray telescope as the tool to make further progress in this area. The key science drivers are that the tracers of strong gravity are mapped on the timescales on which the accretion flow changes so these two effects can be separated. This requires high sensitivity ($\sim 10\text{m}^2$ collecting area), and microsecond time resolution (both to probe the relevant timescales and handle the large photon rates) over a broad bandpass 0.1-50 keV.

3.2 The growth of structures in the Universe

In this area, use is made of the study of luminous accreting black holes as tracers of the growth of structures in the Universe. This overlaps with some of the science issues of theme 2, and is motivated by recent results which show that black holes exist in the centre of most galaxies, and that there is a link between the formation and evolution of the black holes and of their host galaxies. The growth of the black holes via accretion can be traced through their X-ray emission, giving a highly sensitive probe of the formation epoch of massive black holes. This obviously builds on past successes with XMM-Newton.

The next step requires a large X-ray observatory with high sensitivity (10m^2) and high spatial resolution ($\sim 1\text{-}2$ arcsec) to avoid source confusion. Timeliness is also an issue as the growth of the central black holes through mergers can also be studied through gravitational waves. A clear goal is to have simultaneous X-ray observations of a LISA detection of merging supermassive

black holes. The electromagnetic detection would pinpoint the galaxy counterpart, so unambiguously determining distance and breaking the degeneracies of the gravitational wave signature.

3.3 The life cycle of matter in the Universe

The formation of stellar mass black holes can be marked by dramatic supernova events. Capture of debris from the explosion results in extreme mass accretion rates, which can power an ultrarelativistic jet. This can be used to probe the high mass end of the star formation rate out to very high redshifts, tracing back to the epoch of galaxy formation. The debris from the supernova explosion transport both energy and heavy elements into the interstellar and intergalactic medium, heating the gas and suppressing star formation. The chemical abundances of the gas on these large scales can be determined from X-ray line emission in hot gas, and reflect the time integrated supernova rate, while nuclear lines at gamma-ray energies from radioactive isotopes give a snapshot of recent activity. Comparison of the abundances in the local and high redshift Universe will show the evolution of chemical enrichment and the impact of supernova feedback of energy on the growth of large scale structures in the Universe, again with obvious overlap with the science goals in theme 2.

The requirements to probe the abundances of clusters and groups of galaxies out to redshifts 1-2 are for a high throughput (10m^2) X-ray telescope operating in the 0.1-50 keV bandpass, which would build on the XMM-Newton results which extend to $z\sim 0.5$. Much closer, the supernova history of our own galaxy will soon be much clearer through results from MeV lines detected by ESA's Integral mission. New technology developments to build the next generation detectors at these high energies are strongly encouraged (bandpass 100-2000 keV, sensitivity 2 orders of magnitude better than Integral).

Based on the requirements of the scientific objectives of theme 3, combined with the issues addressed in theme 2, **the AWG strongly and unanimously recommends the development of an X-ray observatory-class mission operating in the range 0.1-50 keV, and combining high throughput (10m^2 collecting area) and fast timing capabilities (microsecond time resolution).**

Conclusions

First, the AWG notes the partial overlap of the themes detailed above with some of the Solar System research (mainly theme 1) and Fundamental Physics research (themes 2 and 3). For each theme, the AWG has identified the most powerful tools needed to achieve the progress envisioned. Furthermore, the AWG stresses the importance of a balanced astronomy programme, focussed on observatory-type missions to address broad scientific issues which require long technical developments, and specialised missions to target specific scientific questions, that provide flexibility to adjust the programme to recent scientific developments.

Recognizing the extremely strong scientific cases for studies of extra-solar planetary systems and the understanding of the Universe, as well as the tremendous impact of these two fields on the general public, the AWG recommends that the themes **“Other worlds and life in the Universe: placing the Solar System into context”** and **“The early and evolving violent Universe”** figure prominently in ESA's Cosmic Vision 2015-2025 plan. The European astronomical community is particularly strong in these fields, and the AWG recommends the following roadmap to ensure a leading role for Europe in the discoveries relevant to these

themes.

1. Observatory-type missions

For the very first part of the 2015-2025 decade, two observatory-class missions are recommended:

- **a mid-infrared nulling interferometer for the detection and characterization of Earth-like planets in the Solar neighbourhood.** In order to ensure a timely implementation of such a mission, the AWG gives high priority to the continuation of the present fruitful technology program for this project, and **strongly and unanimously recommends that all steps be taken to ensure that such a mission can be flown as early as possible in the 2015 time frame.**
- **a high throughput, high angular, spectral and time resolution telescope in the X-ray domain for the detection and detailed study of the imprints of the evolution of the Universe, especially those triggered by violent events.** The AWG also gives high priority to the continuation of the present technology program for this project, and **strongly and unanimously recommends that all steps be taken to ensure that such a mission can be flown as early as possible in the 2015 time frame.**

For the second part of the decade, a further observatory-class mission is recommended:

- **a far-infrared observatory for the study of the formation of stars and planetary systems and for the formation and evolution of galaxies.** The AWG recommends that ESA establish a preparatory technology programme in this area. In particular, the trade-off between a far-infrared interferometer and a large single dish should be addressed. **The AWG recommends that such a mission be considered from 2020 onwards.**

2. Specialised missions

The AWG reiterates its unanimous support to a rapid implementation of the Eddington mission, which would constitute an important intermediate step towards the scientific goals formulated in theme 1.

For the first part of the decade (2015-2020), two specialised missions are recommended by the AWG:

- **an optical/near IR wide-field imager to decipher the nature of Dark Energy.**
- **an all-sky CMB polarization mapper for probing inflation.**

Furthermore the AWG recommends that such missions be considered either as dedicated ESA projects or as possible collaborations in similar missions in the NASA programme.

3. Longer term prospective

The AWG supports studies of the following concepts:

- an extreme accuracy astrometry mission for the census of terrestrial planets in the Solar neighbourhood (100 pc), deepening into the Galaxy archeology, and extending the base for distance scale determination,
- a gamma-ray imager in the MeV domain for the physics of Supernovae, isotope abundances, the origin of cosmic rays and of antimatter,
- an optical and UV spectroscopy mission for the search for biomarkers from the atmospheres of terrestrial planets and for detailed studies related to astrophysical cosmology as, for example the warm-hot intergalactic medium,
- a mission devoted to the imaging of exo-Earths, based on the use of large optical interferometers as, or example, in the hypertelescope concept.

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