

CONCLUDING REMARKS: GAIA AND ASTROPHYSICS IN 2015–2020

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1. INTRODUCTION

When Catherine Turon asked me to summarize this conference, I responded positively because I thought it would be a good way to understand all the recent progress on the Gaia project, which for the past four years I had not followed very closely. However, when I saw the title assigned to me in the conference programme, I was slightly taken aback, as Catherine had neglected to mention that I was also supposed to predict the future of astrophysics over the next ten to fifteen years! Upon some further reflection, I realized that this is of course precisely what is needed. It is crucial for any (space) mission that takes of order a decade to construct, to check with some regularity whether the original science goals are still considered relevant, and whether the spacecraft specifications continue to make it possible to achieve these goals.

This was an exciting conference with many high-quality talks, and much additional information in the form of posters, which were summarized in the main session. All aspects of the development of the Gaia mission were covered, from satellite status to data-analysis plans, the activities of the fourteen working groups that support the Gaia Science Team, and previews of the expected scientific harvest. The award of a doctorate *honoris causa* to our ‘Nestor’ Adriaan Blaauw was a particularly noteworthy highlight. I will not attempt a detailed summary, but will instead briefly review the key questions in astrophysics, and the instrumentation on the ground and in space which is being developed to answer these, and will then return to Gaia’s unique place in this overall scheme.

2. PREDICTING THE FUTURE

The key astronomical questions of today are (i) the nature of dark matter and dark energy, (ii) the formation and evolution of galaxies from first light to the present, (iii) the physics of extreme conditions (black holes and gamma ray bursts) and (iv) the formation of stars and planets, and the origin of life. The world-wide astronomical community, together with national science foundations and space agencies, aims to answer these questions by taking observations with telescopes on the ground and in space, supported by interpretative efforts and theoretical work.

The major astronomical space observatories that are active this current decade are the Hubble Space Telescope, the Spitzer Space Telescope, the Chandra, XMM and Integral high-energy telescopes, and, soon to come, the ESA Cornerstone Herschel/Planck. Missions dedicated to specific topics include RXTE, SWIFT, ASTRO-F, COROT, Kepler, and many others in the planning stage.

On the ground the 8–10 m class optical/infrared telescopes (Gemini, Keck, Subaru, VLT) are being equipped with a full arsenal of instruments, including many that take advantage of progress in adaptive optics, and are also being linked interferometrically (e.g., VLTI) to obtain milli-arcsecond resolution. Numerous large-scale surveys are available, including 2MASS, GSC-II, USNO-B, the 2dF and Sloan Digital Sky Surveys, and more are being planned, including the SDSS extension SEGUE to study Milky Way structure. Many 2–4 m class telescopes now focus on wide-field imaging surveys (MegaCam on the CFHT, Omegacam on the VLT Survey Telescope, and VISTA). The RAVE project aims to obtain millions of radial velocities for stars in the Galaxy by multi-fiber spectroscopy. Following the success of MACHO, EROS and OGLE, a new generation of synoptic facilities is being planned, with PanSTARRS already under construction. LOFAR will provide a major step forward for objects which emit extremely long-wavelength radio waves.

The next decade will see the full power of the 8–10 m class optical/infrared telescopes exploited with second generation instruments and interferometric links, the completion of the first ground-based global observatory ALMA, and the launch of SIM and the James Webb Space Telescope. Construction of Extremely Large Telescopes for the optical/infrared (GMT, TMT, and OWL), and the Square Kilometer Array will start. The proposed 8m class Large Synoptic Survey Telescope could provide deep imaging of (one hemisphere of) the entire sky every four nights. It could well be complemented by imaging from space to detect extra-solar planets by their microlensing signature (MPF), and to detect supernovae for studies of dark energy (JDEM). LISA will detect the gravitational wave signature of coalescing black holes, and the very ambitious TPF-C mission could provide images of extra-solar planets later in the decade. And finally, Gaia will provide an all-sky photometric survey from launch in 2012, with the exquisite astrometry and the radial velocities continuously improving until the complete measurements will be available in 2018.

3. GAIA SCIENCE

3.1. Science Case 2000

The top-level summary of the Gaia science case as presented to ESA on 13 September 2000 in Paris stated the following. Gaia will determine:

- when the stars in the Milky Way formed;
- when and how the Milky Way was assembled;
- how dark matter in the Milky Way is distributed.

Gaia will also make substantial contributions to:

- stellar astrophysics
- Solar System studies
- extra-solar planetary science
- cosmology
- fundamental physics

This is provided by a stereoscopic census of the Milky Way with the following top-level specifications:

- astrometry for all objects with magnitude $G < 20$ with accuracy better than $10 \mu\text{as}$ for the parallax, and $10 \mu\text{as/yr}$ for the proper motion, for all stars brighter than $G = 15$. This requires on-board detection, and is *the key* to the success of the mission (Astro);
- radial velocities for (nearly) all objects with $G < 17$, with an accuracy between 2 and 10 km s^{-1} (depending on spectral type). These provide the crucial third component of the space motion of the objects, and are important for the measurement of perspective acceleration influencing the proper motions. The spectroscopy from which the radial velocities are derived also provides crucial astrophysical diagnostics of the objects (RVS);
- broad- and medium-band photometry for all objects with $G < 20$. The broad-band measurements (BBP) are critical for chromatic correction, which otherwise would limit the astrometric accuracy. Together with the medium-band photometry (MBP) it provides astrophysical diagnostics, including an estimate of extinction, effective temperatures accurate to about 200 K, and [Fe/H] accurate to 0.2 dex.

A more detailed description of the Gaia science case and specifications can be found in Perryman et al. (2001).

3.2. The Milky Way

Halo. The key fossil record of the formation of the Milky Way is to be found in the Galactic halo (Freeman & Bland-Hawthorn 2002). The overall aim is to reconstruct the merger and accretion history from Gaia's unbiased stereoscopic census by identifying the various star streams and tagging them by the metal abundance and ages of the stars. RAVE and SDSS/SEGUE, if funded, will make good progress towards delineating substructure in the Galactic halo. However, these surveys will provide only one component of the three-dimensional space motion, and for <1% of the stars to be measured by RVS.

Disc. The Gaia observations of stars in the Galactic disc will provide an unprecedented record of the star formation history in the disc of an average spiral galaxy. It will provide internal motions of star forming regions and star clusters, the initial mass function, the full census of binaries, and determine the age-metallicity relation in the disc. The classical work by Edvardsson et al. (1993) and Nordström et al. (2004) provides a small preview of what can be achieved in this way.

Bulge. The Galactic bulge is the nearest (barred?) spheroidal galaxy component, and hence it is important to study in detail its resolved stellar population and internal dynamics. Crowding and extinction conspire to make only some windows available for study. The Gaia measurements will cover a useful fraction of the Bulge, but some of the science questions will be addressed earlier by studies in very small fields, e.g., by combining multi-epoch HST imaging with ground-based follow-up spectroscopy using multi-fiber or integral-field spectrographs.

Gaia will provide estimates of ages and metallicities for many of the stars it observes. These are crucial for unravelling the formation history of the halo and the disc. The presentations at this conference showed that much effort is still needed to try to improve the accuracy of the ages and the [Fe/H]-values, and the effect of variations of $[\alpha/\text{Fe}]$ on these, as provided by the data from the MBP and the RVS. Of course, once kinematic subgroups or streams have been identified in the kinematics, their members can be followed up with targeted higher-resolution spectroscopy from the ground. In all of this the determination of the extinction is critical. This may well need additional information from all-sky HI surveys and the 2MASS infrared maps, and is likely to need further preparatory work with wide-field imaging telescopes such as VST and VISTA.

Dynamics. A detailed model of the Galaxy needs to bring the star counts and three-dimensional kinematics into harmony by using Newton's laws of motion and gravity. When applied to the full Gaia data this approach has massive discriminating power, which will allow a dynamical determination of the gravitational field of the Galaxy, and provide the distribution of dark matter.¹ James Binney discussed three approaches to do this, and noted that while the Schwarzschild (1979) method is currently the most developed, with many applications to model nearby galaxies, there are two alternatives which merit further scrutiny, namely the 'made-to-measure N-body method' and the 'Oxford torus machine'. Developing these methods to the point where they can in fact deal with (do justice to) the entire Gaia data set is a major undertaking, and needs to start now. Much experience in this area is available in Europe, and a coherent programme in this direction is an excellent example of a preparatory effort to analyse and interpret the data that is beyond the scope of the Gaia project itself, but is critical for the scientific success of the mission. This is also an ideal project for further strengthening the European Research Area, and lends itself naturally to network support from the EU.

¹If it turns out that Newton's law of gravity is modified at low accelerations (Bekenstein 2004), the Gaia data will be equally useful.

3.3. Stars, the Solar System, Extra-Solar Planets, Cosmology, Transients, & Fundamental Physics

Stellar astrophysics. Gaia's astrometric accuracy is such that more than 10^7 stars will have distances to better than 1%, and hence absolute luminosities to better than 2% (provided the extinction correction is accurate). As many as 10^8 binary stars will be detected, covering, at last, the full range of periods and magnitude differences. Staffan Söderhjelm expects good orbital solutions for 5×10^5 systems, which will give accurate masses. In combination with seismology from COROT, this will allow absolute calibration of stellar models over the entire Hertzsprung–Russell Diagram with unprecedented accuracy, as a function of metallicity. This is a unique contribution of Gaia which affects *all of astrophysics*, including the distance scale, but more importantly, the calibration of stellar population models. The VLTI will take the first steps in this direction, but will be limited to at most a few hundred objects. As Yveline Lebreton made very clear, a meaningful comparison with the observations will require much preparatory work to further refine the (three-dimensional hydrodynamic) stellar models, as many physical effects need to be understood in detail.

The Gaia photometric survey will reveal many known and new variable stars, even though the cadence of observations is not optimized (nor should it be) for the detection of such objects. Much of the anticipated science may well be done before Gaia, by OGLE, PanSTARRS, and the LSST. It will be difficult however for ground-based telescopes to reach the exquisite homogeneity of the multi-band photometry that Gaia will bring by virtue of its continuous scanning and its location above the Earth's atmosphere. The preparation for the Gaia data on variable stars will benefit from the investment in developments of algorithms provided by, e.g., the OGLE collaboration.

Solar System. In the next decade much work on asteroids and moons in the Solar System will be done from the ground. Gaia's astrometric accuracy will allow unique contributions to be made to the dynamics of the Solar System, and will help identify Earth-crossing dangers. The Gaia photometry of asteroids will surely be mined, but work on variability will suffer from the limitations mentioned in the previous paragraph. The groups preparing for the analysis of the Gaia data will also be in a good position to benefit from data of PanSTARRS or the LSST.

Extra-solar planets. Gaia will provide a unique window on the population of extra-solar planets in our Galaxy. Didier Queloz demonstrated that the Gaia discovery space in the plane of semi-major axis a versus mass m coincides with territory already explored with the radial velocity method, transits, and, in the future, by interferometry with VLTI/PRIMA and SIM. However, the complete Gaia census is expected to provide accurate orbits for about 5000 systems, more than an order of magnitude larger than can be expected by the combination of all other methods in the same time frame. This makes the Gaia contribution to this exciting and rapidly developing field unique even in fifteen years time, and will allow a much increased understanding of the population of planets as a function of the properties of the parent star.

Extragalactic science and cosmology. Gaia will measure fairly accurate proper motions of stars in the nearby spheroidal satellites of the Milky Way, and perhaps also in M31 and M33 by using globular clusters and the brightest AGB stars. This will provide the dynamical distance, internal orbit structure, and constrain the dark matter content. Ground-based work on nearby globular clusters has already demonstrated the power of three-dimensional kinematics (van de Ven et al. 2005). At cosmological distances, Gaia will provide a large and homogeneous data set on quasars. These will define the global reference frame and will also allow an independent determination of the absolute three-dimensional acceleration of the Sun. The astrometric selection of quasars might provide some surprises. It is important to establish what other quasar science could be done beyond the SDSS.

Transients. Wyn Evans discussed the possibility to detect transient events with Gaia. This will require special 'science alert' software on the ground, which may require either *a priori* information or use the Gaia data from the first half year of the mission to establish the 'steady' sky content to $G = 20$ at Gaia's spatial resolution. Given the limitations of the ground-station coverage, with an anticipated data download once a day for about eight hours, there will be limitations to the possibilities for rapid follow-up of the fastest events. For transients discovered by other means, it will be possible to go back to the Gaia data afterwards, and check whether the on-board software in fact detected something. The value of the expected detection of, e.g., as many as 5×10^4 supernovae is hard to judge today. If JDEM is launched, it may provide similar numbers well before 2018. Dedicated ground-based projects to measure the dark energy parameters in other ways may also get there before Gaia.

Fundamental physics. One of the aspects of the Gaia mission that continues to impress me tremendously is the level to which the astrometric measurements are influenced by general relativistic effects at the μas level. This was beautifully illustrated by the time sequence of the expected light-bending in the Solar System, caused by the moving planets. Sergei Klioner's authoritative presentation inspired much confidence that all these effects are understood and can and will be incorporated in the data reduction. This will allow measurement of various post-Newtonian parameters with remarkable accuracy.

3.4. Science Case 2015–2020

The top-level science goals for Gaia are unchanged from those articulated in 2000. The study of the formation and evolution of the Milky Way by means of a stereoscopic census with μas accuracy also delivering stellar astrophysical parameters continues to be a crucial complement to studies of galaxies at high redshift and in the nearby Universe. Any science goals that require μas astrometry will remain unique (e.g., the massive census of extra-solar planets). The need for Gaia is arguably stronger than in 2000, because of the unfortunate demise of DIVA and FAME, which would have done some of the science, and the modest number of pre-selected targets to be observed with SIM, albeit with great astrometric accuracy.

4. THE GAIA OBSERVATORY

The core of the Gaia spacecraft is the Astro instrument. The poster with the real-size layout of the 1.5 Gpixel focal plane was an impressive visual reminder of the technological challenge. The presentations inspired confidence that the focal plane can be assembled and tested, and will be able to deal with almost anything that the sky offers (including the observation of the occasional bright star without overloading the system). It is also clear that minimizing radiation damage is critical.

The radial velocity spectrograph RVS is well-defined, and a simulator is in place (Katz et al. 2004). Impressive progress has been made on the ground with the RAVE precursor. This allows hands-on experience with the Ca triplet spectral region, testing parts of the data analysis software, including the recovery of stellar atmosphere parameters in addition to the radial velocity, and already provides a preview of the RVS science. This is an excellent way to prepare for the Gaia mission.

The details of the photometric system (BBP and MBP) are still under discussion. It was interesting to hear of the work by the photometry working group which now, finally, brings them close to a decision on which bands to adopt. This should be done soon, so that the group can then concentrate on optimizing the algorithms to get the highest accuracy on the derived stellar parameters. It will be very useful to equip a ground-based wide-field imager with the chosen filters, and develop experience.

Much progress has been made in developing the complex software for the on-board detection and data handling. Tests with OGLE and HST images of crowded fields show very promising results, but the limited on-board cpu power and the telemetry capacity remain a challenge. The global iterative solution to obtain the astrometric measurements has been shown to work. Much effort is devoted to steadily build up the (simulation of) the end-to-end Gaia system, with many groups providing components of the software. This entire effort is a textbook example of a distributed European activity, with links to the development of the GRID.

Finally, a few words about outreach. The Gaia project provides many possibilities for education and outreach activities, from ‘The little books of Gaia’ to high-school exercises which attract students to the physical sciences (see <http://www.rssd.esa.int/Gaia>). The main science goals are of general interest, in particular the search for extra-solar planets. The Gaia data also make it possible to simulate travelling through the Galaxy, so that it is feasible to create the legendary ‘astrometrics lab’ from Star Trek Voyager, run by Seven-of-Nine, 357 years ahead of its time (which relates to points made by Jos de Bruijne and Xavier Luri during this conference). Outreach is and should be an integral part of any (space) project. Gaia in particular provides a key opportunity to go well beyond the now standard press releases to in-depth efforts, supported by ESA together with national programmes, to engage the wider European public in the excitement of scientific discovery.

5. GAIA, A EUROPEAN PROJECT

This conference demonstrated that the initial Gaia concepts for μas astrometry from space, developed in the mid-nineties by Lennart Lindegren and Michael Perryman, and subsequently worked-out in detail by the Gaia Science Advisory Group and approved by ESA, have now led to a coherent effort by a well-organized, diverse, and increasingly sophisticated team consisting of more than 250 European astronomers. The team combines the experience of senior astronomers, some of whom helped make Hipparcos such a resounding scientific success, with the energy and drive of young scientists and engineers. The group works closely with ESA and the project has strong industrial involvement. The entire effort is overseen by the Gaia Science Team under the eminent leadership of the project scientist Michael Perryman.

The team has made much progress in the past four years. The three Gaia instruments have been defined in great detail, and there is a much improved understanding of the required algorithms and the full scope of work. Much of this effort is funded locally. The Gaia science case remains very strong and broad, but depends critically on maintaining the specifications set in 2000, and summarized in Section 3. The mission is very challenging—as an ESA Cornerstone should be—but the team shows all the signs that it will be able to pull this off. This will be a significant achievement for astronomy world-wide.

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