AstroTalk: Behind the news headlines of October 2011

Richard de Grijs (锐何思)
(Kavli Institute for Astronomy and Astrophysics, Peking University)

Imagine what you could do with a 1000 megapixel camera…

The digital camera I prefer to use when I expect to encounter good photo opportunities, a single-lens reflector (SLR), is equipped with a 9 megapixel (MP) optical sensor array or "charge coupled device" (CCD). It was a state-of-the-art device when I acquired it a few years ago, although I recently saw advertisements for affordable 20 MP cameras, so technology developments have clearly moved on. These numbers simply mean that the respective CCDs contain 9 and 20 million picture elements (pixels), which are the smallest units in a two-dimensional digital raster that can be controlled individually. In practice, the CCD housed in my SLR camera consists of a rectangular raster of 3696×2616 pixels.

This month, we learnt that the CCDs constructed for installation in the European Space Agency's *Gaia* satellite are ready for delivery. *Gaia*'s main work-horse detector is also a 9 MP CCD, but that's where the similarity with my own digital camera ends: instead of a single 1966×4500 pixel chip, the satellite will be equipped with 106 of these 9 MP sensor arrays, arranged in a rectangular pattern, so that the final camera will be equivalent to a 1 gigapixel device! That's 1 billion pixels or 1000 MP… Imagine having one of those with you on your next photo shoot… But before this article prompts you to consider buying a new camera with a higher megapixel count than your current photographic companion, I should point out that for most practical purposes in everyday life, a 6 MP camera will do just fine: for your photographic needs, sharpness does not define image quality, nor does the number of pixels define sharpness. If you want to take really good digital pictures, colour and tone are a lot more important, and so is the photographic technique you adopt to avoid image blurring.

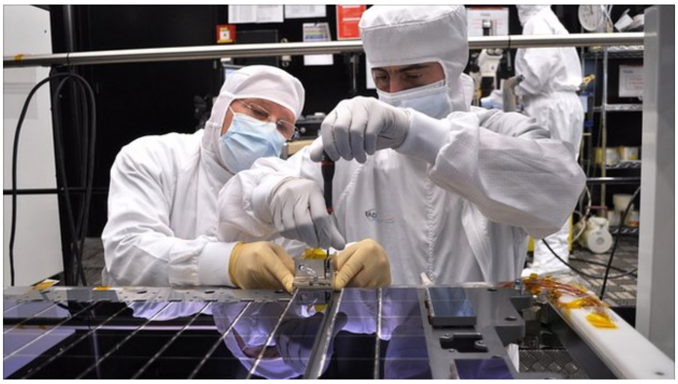

Figure 1. The CCDs are arranged in rows across a support structure made of feather-light silicon carbide. (http://www.bbc.co.uk/news/science-environment-15242383)

Let me return to *Gaia*'s 1 gigapixel camera. To illustrate how technologically ambitious this project is, I point out that the next largest space-based camera is currently flying on board NASA's *Kepler* planet-hunting spacecraft. *Kepler*'s camera consists of 42 CCDs of 2200×1024 pixels each, resulting in a 95 MP detector. In comparison, *Gaia*'s detector is more than ten times larger, at least if we consider the number of pixels. Nevertheless, the entire detector array covers less than half a square metre, so it – and the satellite it will work with – fits snugly inside the payload bay of a Russian *Soyuz* rocket when it will be launched in late 2013. The European Space Agency decided to use the *Soyuz* instead of its own *Ariane 5* launch vehicle simply because the Russians charge less.

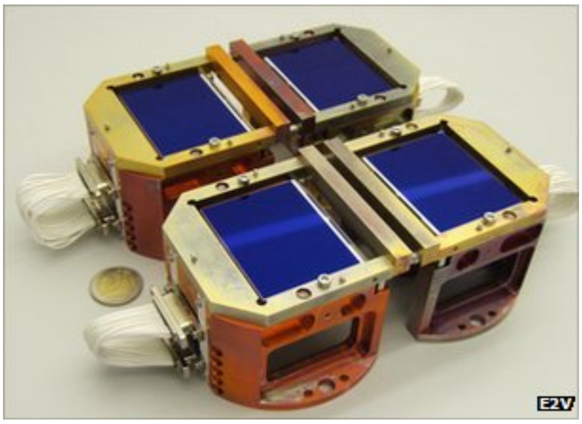

Figure 2. Individual CCDs in their handling containers. (http://www.bbc.co.uk/news/science-environment-15242383)

In May of this year, I was invited to present a scientific paper and lead a discussion at a scientific conference in southern Spain devoted to the promise of *Gaia* and its science, where we heard that all aspects of the mission's planning are running smoothly. *Gaia* will fundamentally change our understanding of the Universe, in more ways than one. Its primary goal is to study the structure and evolution of our Milky Way galaxy by linking the spatial distributions and motions of stars with their astrophysical properties such as their masses, chemical compositions, sizes and the strength of their surface gravity. Determining three-dimensional distributions and space motions for large numbers of stars enables tracing the Milky Way's gravitational potential (which corresponds to the three-dimensional mass distribution, including that of the so-called "dark matter" thought to dominate stellar and galactic motions at large distances from the nuclei of galaxies) in greater detail than ever before. Determination of very accurate distances to huge numbers of stars will allow stringent tests of stellar-structure models and drive improvements of theoretical models of stellar atmospheres, interiors and evolution.

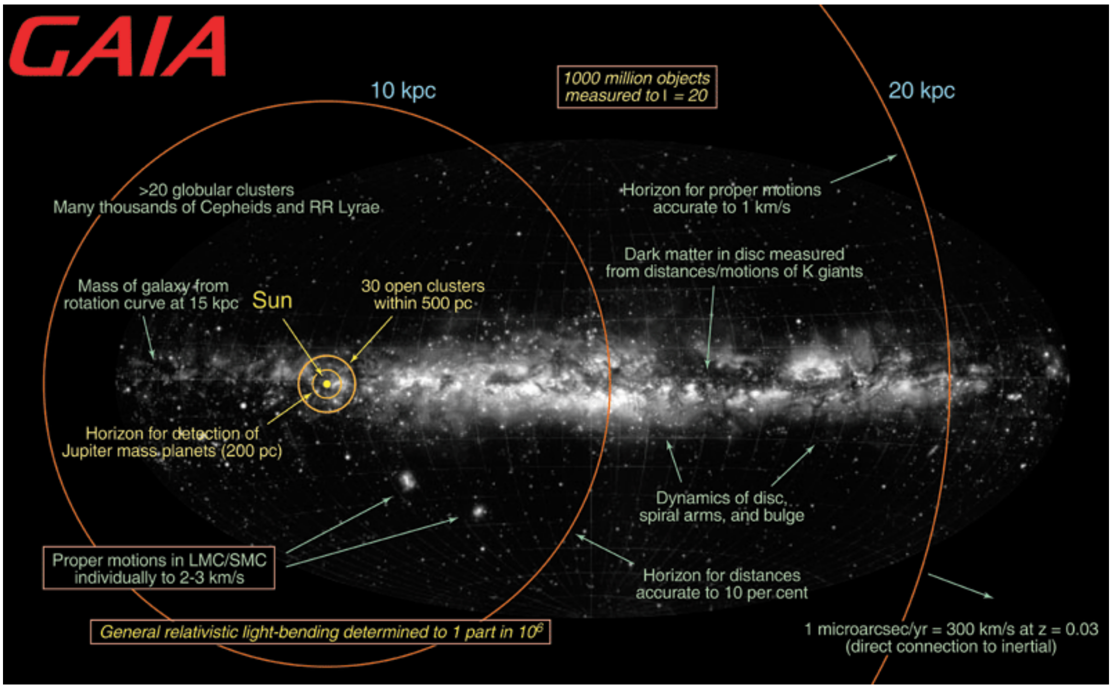

Figure 3. Schematic diagram showing the distances out to which *Gaia* will contribute to our knowledge of the Milky Way. *(**Credit**: European Space Agency/C. Carreau.)*

And because *Gaia* will track anything that passes across its CCDs, it will likely also see countless objects that have thus far gone unrecorded, including planets orbiting stars in other solar systems, and faint stars or so-called "brown dwarfs" that never quite fired into life. It will, additionally, play a crucial role in solar-system physics, such as through detection of many tens of thousands of new minor planets. And even new objects orbiting the Sun beyond the orbit of Neptune, including Plutinos (small rocky bodies, mostly in the outer Solar System, named after their prototype Pluto), may be discovered. Estimates suggest that *Gaia* will detect some 15,000 planets outside our solar system by looking for tiny movements in stellar positions caused by the minute gravitational pulls of these planets on their host stars. The mission will also test Einstein's theory of gravity – General Relativity – by checking the perturbing effect of the Sun's gravity on starlight to approximately 2 parts in a million. These are truly exciting times for scientists working in a large number of related fields in astrophysics, including myself and some of my colleagues at the Kavli Institute for Astronomy and Astrophysics at Peking University.

All of these scientific objectives crucially depend on the determination of reliable, precise and accurate distances to the objects we want to study in detail; in other words, distances that are *both* correct in an absolute ("systematic") sense *and* are only affected by very small random ("statistical") uncertainties. This is the essence of the *Gaia* mission. As in most of the physical sciences, robust results in astrophysics depend first and foremost on obtaining physical quantities with well-understood and small statistical "error bars" and negligible systematic offsets. (***Statistical*** uncertainties can usually be minimized by obtaining more data points, while ***systematic*** errors introduce offsets that may not be obvious at first but will surely give incorrect results that cannot be fixed at a later stage.) After launch and successful initial checks of its system performance in low Earth orbit, the spacecraft will be directed to a location at some 1.5 million kilometres from Earth, beyond the Moon's orbit, where it will orbit the Sun as a new, artificial solar-system body.

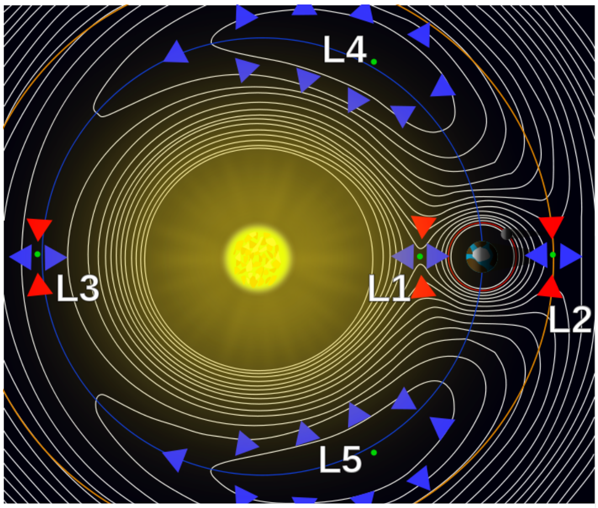

Figure 4. Contour plot of the gravitational potential ("force") in the Sun–Earth system, with the five stable Lagrange points indicated (L1–L5). *Gaia* will be sent to L2. The red and blue arrows show the direction of the gravitational pull. *(**Credit**: Wikipedia)*

The satellite's destination is L2, one of the five Lagrangian points (L1–L5) in the Sun–Earth system, where a small object that only responds to gravitational forces can be in a stable orbital position relative to two much more massive bodies. In the L2 point determined by the Sun–Earth system, any object will orbit the Sun at the same rate as the Earth, which makes their operation much simpler than in many other locations. This has been taken advantage of by a number of man-made science satellites, including NASA's *Wilkinson Microwave Anisotropy Probe*, the European Space Agency's *Herschel* and *Planck Space Observatories*, and the Chinese *Chang'e 2* probe. In addition to *Gaia*, the *James Webb Space Telescope* will also be sent to the Sun–Earth L2 point.

Because of its stable orbital position, *Gaia* will be able to determine very accurate, direct distances to up to a billion stars in the Milky Way and slightly beyond using the well-established technique of measuring annual parallaxes. As the probe orbits the Sun, the nearest stars will appear to trace equivalent elliptical orbits against the background stars, which appear to remain in fixed positions because of their much greater distances. The angular size of the apparent ellipse (referred to as the "trigonometric parallax angle") depends on the distance to the star of interest. This technique was first applied in 1838 by the German mathematician and astronomer Friedrich Bessel, who measured a distance of 10.4 lightyears to the star 61 Cygni (9.6% too small compared to the more accurate distance measurements we have access to today). Before Bessel's publication, the Baltic–German astronomer Friedrich Georg Wilhelm von Struve had announced a parallax measurement for Vega (α Lyrae), which was surprisingly close to the currently accepted value. However, he later almost doubled his determination and, thus, cast significant doubt on his result, so that Bessel is now generally credited with the first published parallax measurement.

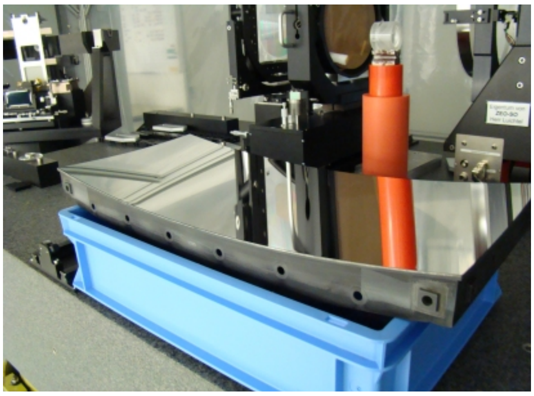

Figure 5. One of the *Gaia* mirrors. *(**Credit**: European Space Agency)*

In practice, using observations from telescopes on Earth, this method is applicable out to distances of approximately 300 lightyears, but if we really care about minimizing the associated error bars, a realistic distance limit is of order 60 lightyears. This limits the method's applicability to only a few hundred stars, while distance uncertainties increase rapidly beyond a few lightyears. Achieving significant gains in *astrometric* precision (precision of coordinate determinations on the sky) with respect to ground-based measurements requires dedicated space-based observatories covering large angular swathes of the sky. The European Space Agency has an excellent track record in this area: it operated the pioneering *Hipparcos* spacecraft between 1989 and 1993, which produced a catalogue of highly accurate parallax (and, hence, distance) measurements of some 118,218 stars within roughly 300 lightyears from the Sun. *Gaia*'s mirrors will collect thirty times more light and measure star positions and motions two hundred times more accurately – this is where the larger number of smaller pixels really provides a significant advantage. The mission will improve on the *Hipparcos* achievements by producing a ten times larger catalogue containing significantly more precise and accurate measurements out to much greater distances.

Like *Hipparcos*, *Gaia* will measure large angles between more than 200 million carefully selected objects on the sky using a telescope with two apertures, aimed at directions separated by 106.5 degrees. By scanning the sky in great circles, one can calibrate the angle between the two fields of view to high accuracy and, hence, obtain *absolute* parallax angles and distances. (***Absolute*** values are usually much harder to obtain than ***relative*** measurements, because one has to take care to avoid any intrinsic systematic uncertainties.) This will enable construction of the most accurate three-dimensional model of the Milky Way ever obtained.

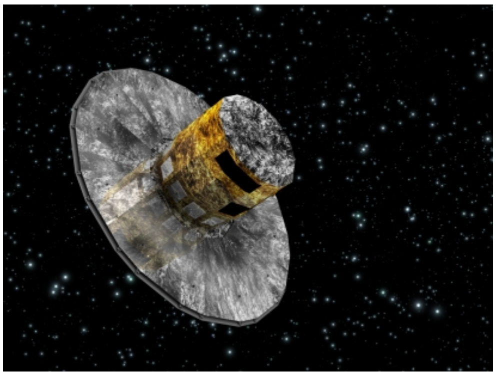

Figure 6. Artist's impression of the *Gaia* spacecraft in flight. *(**Credit**: European Space Agency)*

However, we are not quite at the point of delivery. *Gaia* is certainly a long-term project. The timeline from the mission's first approval to launch will be 13 years – if the launch date does not slip. Collecting, processing and initial analysis of all the data for its star catalogue will probably take another seven or eight years. And then there is the sheer amount of data that needs handling. "The raw data that has to be collected is about 100 terabytes, and when all the data are processed in the archive we are talking about up to one petabyte", says Giuseppe Sarri, the European Space Agency's *Gaia* project manager – that's a billion gigabytes, an almost incomprehensible amount of hard-disk space. "For the analysis, a supercomputer will be needed to get out all the numbers." Several teams spread across Europe are currently extremely busy preparing for the mission, and that includes getting the computational set-up ready for processing of the expected data deluge.

To beam all of *Gaia*'s observational data to the dedicated ground stations will require quite an impressive downlink capability: about 5 Mbit per second during its daily passes, similar to many home broadband connections in the developed world today, but remember that this has to be sent from 1.5 million kilometres away... At the end of its five-year mission, the information will occupy over 30,000 CD ROMs – filled with one billion celestial objects – and be freely distributed to the international astronomical community. We are eagerly looking forward to getting our hands – and those of numerous students and junior researchers – on the anticipated treasure trove of data!