The first picture of a new world

The image released in September 2008 that shows the star 1RXS 1609 with its 8 Jovian mass planet (above the title). This is the first image of a planet not belonging to our own solar system. [Gemini Observatory]

There were 490 known exo-planets as of 27th August 2010, a number bound to increase enormously thanks to new space telescopes dedicated to this kind of research, especially Kepler. Meanwhile, on Earth, there are still those that fuel the myth of the tenth planet, without realizing that reality has long since surpasses both the most fanciful minds and the most advanced models of planetary system formation.

"We are all in the gutter, but some of us are looking at the stars"

Oscar Wilde

Twenty years ago, or even less, it was only possible to imagine the day when we would see directly the first planet belonging to a planetary system other than our own. Now that all this has become a reality it seems that few realize its scientific, philosophical and even religious importance.

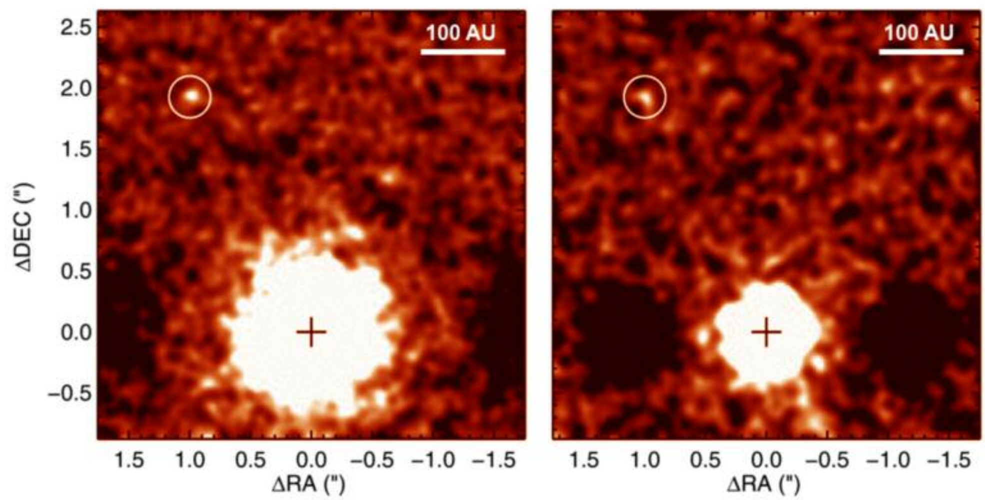
One thing was to imagine, and it was done for centuries, the existence of very distant planets, but it is quite another thing to have the image on a screen or printed on paper.

Today, human beings are accustomed to rapidly consume anything, even the great intellectual achievements, and that which today is breaking news (almost always given superficially) tomorrow is an old argument warranting no further discussion. Seeing the image of the first confirmed exoplanet and knowing that it is in orbit around a star other than the Sun is something more than a mere curiosity, and knowing more about how astronomers reached this important milestone might be of some interest.

The story of the first "live" planet discovery officially started on 27th April 2008, with three researchers at the University of Toronto who were working with the Gemini North telescope in Hawaii. This is an 8 metre diameter instrument located on the 4200 metre summit of the dormant volcano, Mauna Kea, a site that hosts numerous other large instruments.

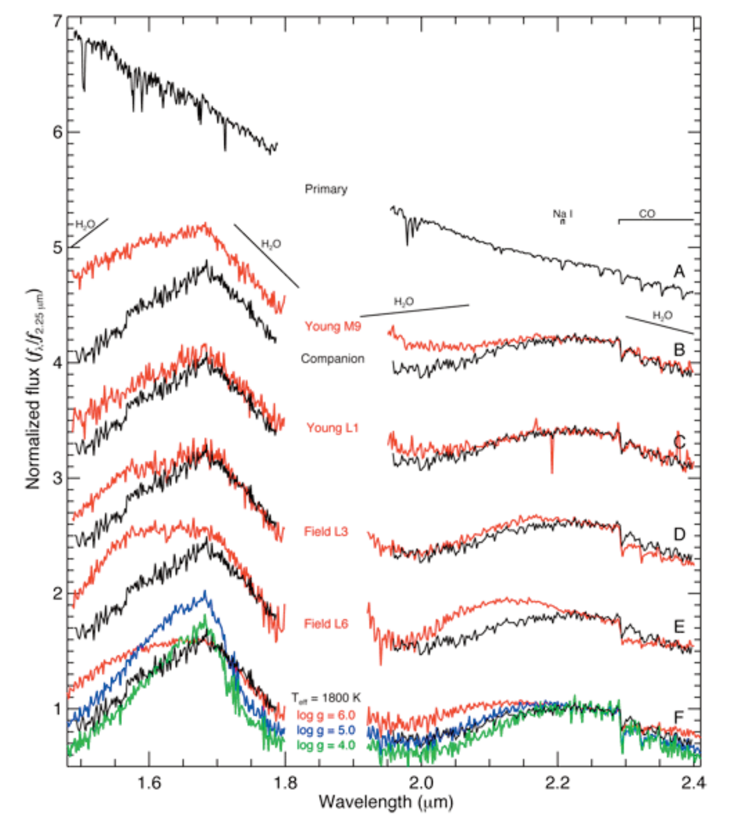
As the name suggests, the Gemini North telescope has a twin, Gemini South, in the southern hemisphere, on the Cerro Pachón in Chile. Both are equipped with the latest technology and together they cover the entire sky from the visible to the near infrared. Together they are at the cutting edge of astrophysical research.

1RXS 1609 and its planet imaged in the infrared at 3.05 and 3.78 μm that were useful in the determination of the planet's mass. The dark patches are artifacts introduced during the data reduction. [Gemini Observatory/AURA/David Lafrenière (Univ. of Montreal), Ray Jayawardhana and Marten H. van Kerkwijk (Univ. of Toronto)]

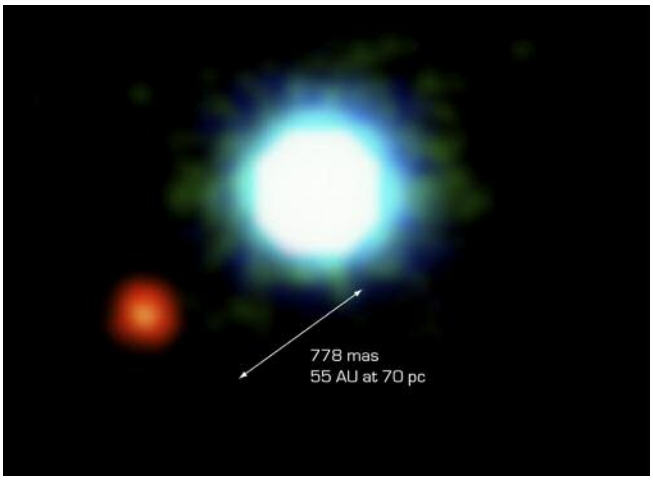


Amongst the nations involved in the building and running of the two twins is Canada (in addition to the USA, UK, Chile, Australia, Argentina and Brasil) whose researchers have the right to use them for their research programs. Amongst those in progress in 2008 was a survey of young stars belonging to the Upper Scorpius association. This contains 2525 stars with masses greater than 0.1 solar masses, born in a single nebular complex between 4 and 5 million years ago, and distributed over an area of about 150 square degrees.
The survey was carried out by David Lafrenière, Ray Jayawardhana and Marten H. van Kerkwijk (of Toronto University) who, taking advantage of the capabilities of the Near-Infrared Imager (NIRI) and the adaptive optics system, Altair, in use at Gemini North, aimed to detect the very faint emission from the companions of the members of the association. The point was to see if such young stars were more frequently accompanied by small stars, brown dwarfs or giant planets.
The choice of observing a vast population of young stars was obviously not chance: possible companions would also be younger so that their gravitational accretion should have ceased only recently, or just be finishing; which implies hotter core temperatures and consequently hotter primordial atmospheres.
All of this translates into abundant infrared luminosity, that also allows their relatively small companions to be detected by the best ground-based instruments. If one then chooses to look at stars similar in mass to the Sun, or smaller, then the chances of success are even higher.
In April 2008 Lafrenière and colleagues had observed about 85 stars of the Upper Scorpius association, only a small fraction of the total population, but enough to detect one, 472 (±65) light years away, that immediately attracted the attention of the three astronomers. Referred to as 1RXS J160929.1-210524, 1RXS 1609 for short, that star, in itself was unremarkable: spectral type K7V (±1), photospheric temperature 4060 (+300/-200) K (Kelvin), mass 0.85 (+0.2/-0.1) solar masses, diameter about 1.9 million km, age around 5 million years.
However, in a series of images taken on 27th April, and repeated on 21st June, a second body could be seen (after a

series of sophisticated analyses) 2.22" from 1RXS 1609, corresponding to 330 AU (astronomical units) at a position angle of 27.7 degrees.
It was certainly too faint to be a star, but at first glance was also too far from 1RXS 1609 to be a planet.
The same 21st June Lafrenière, Jayawardhana and van Kerkwijk begin infrared spectroscopic analysis, and continue on 21st and 24th August (telescope time allocation being what it is...). They immediately notice a strong absorption line due to water vapour in the H (1.65 μm) and K (2.2 μm) bands, a significant presence of CO (carbon monoxide) beyond 2.29 μm, and molecular hydrogen. The type of spectra obtained are consistent with an extensive atmosphere and with a relatively low surface gravity, exactly as expected for a body of planetary dimensions (or larger) at the end of their gravitational collapse phase.
Comparing the colour of the object in the J (1.25 μm) and K bands with that of brown dwarfs from the same association, the three Canadians assigned a spectral class of L4 (+1/-2) that corresponds to a surface temperature of 1800 (+200/-100) K. For comparison, Jupiter, that has been cooling for 4.5 billion years, has a temperature of 160 K (-113°C).
Given the spectrum, the temperature and the age of the companion of 1RXS 1609 (assumed to be coeval and assigned the name 1RXS J1609-2105b) Lafrenière and colleagues took the next step, that is, determining the mass, calculating theoretically the initial temperature and the cooling rate over the 5±1 million year time frame. The result was 0.008 (+0.004/-0.002) solar masses, equal to 8 Jovian masses, with a diameter of 238,000 km.
At that point it was obvious that it could only be a planet, because the mass limit for brown dwarfs is 13 Jovian masses. At the same time, the enormous distance from its star, 330 AU, corresponding to about 50 billion km (11 times the distance of Neptune from the Sun) left some doubt as to whether the planet was actually gravitationally bound to 1RXS 1609.
There was no precedent for this situation, largely because all the other techniques used to find exo-planets (monitoring of the star's radial velocity, transits across the stellar disk and micro-



The spectra of 1RXS 1609 (Primary, A) and its planet (Companion, from B to F) compared with those of two young brown dwarfs (M9 and L1, B and C) and two older, cooler brown dwarfs (L3 and L6, D and E). The similarity between the planet and the smaller, young brown dwarf (L1) is evident. The distinctly triangular shape of the spectrum at higher frequencies indicates a low surface gravity, consistent with an object at the end of its accretion phase. The spectra labeled F show some model spectra for various temperatures, and confirm the temperature of 1800K derived for the planet, confirming also its young age. [D. Lafrenière, R. Jayawardhana, M. van Kerkwijk]



In 2004, using the "Yepun" 8.2m telescope of the European Southern Observatory's VLT, an approximately 5 Jovian mass object was photographed apparently in orbit around a brown dwarf (called 2M1207). This dwarf star is 230 light years away and is 42 times less massive than the Sun. The object was not classified as a true planet however, because it is not actually in orbit about the star. [ESO]

lensing) are more efficient when the companions are more massive and closer to their host star. Only around brown dwarfs had very distant companions been found. The only previous case around a true star was that of Fomalhaut, discovered back in 2004. In this case the probable planet (confirmed only 4 years later) was still in formation within a protoplanetary disk, and was, in any case, only at about 1/3 of the distance of 1RXS J1609-2105b from its star.

But even more pressing than the distance itself was (and is) the fact that no model of planetary system formation predicted the presence of planets so far from the host star. This failure in the models was added to various others that had become apparent over the years, and will inevitably lead to a serious revision of these models, or a least to a more flexible version.

It was fundamental to demonstrate the gravitational connection between 1RXS 1609 and its putative companion, because otherwise the proximity could simply be a projection effect. May be it was just passing, after having been expelled from some other planetary system as a result of a close encounter with a similar body, during migration towards a stable orbit. This is a possibility already encountered elsewhere. To exclude this possibility, Lafrenière, Jayawardhana and van Kerkwijk calculated the possibility of such a chance alignment, and even using rather extreme assumptions concluded that there was only about a 1 in 2000 chance that a wondering planet should find itself projected so close to 1RXS 1609.

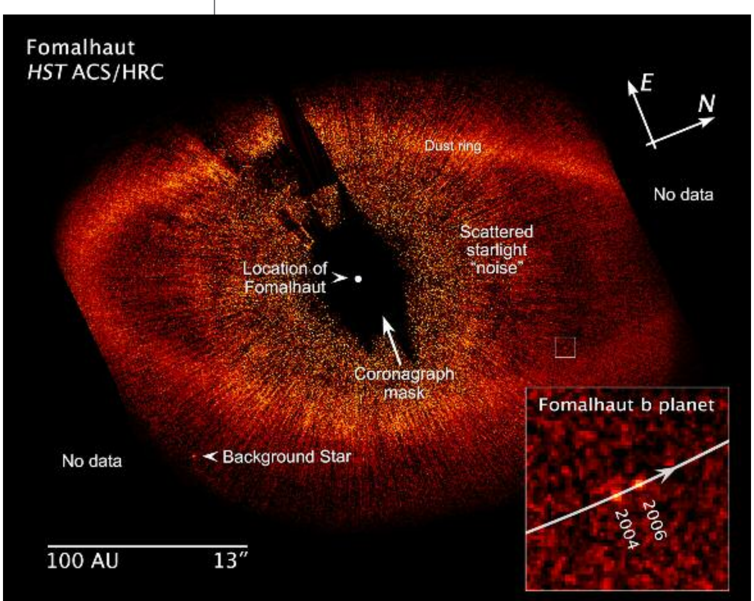
The final proof of a physical link could only come from the simple translational motion in space of the objects. This is not easy to measure given the low velocity dispersion of the Upper Scorpius association, but as it in known (-11.2±1.5 mas/yr in R.A. and -21.9 ±1.5 mas/yr in Dec.) it was possible to predict, taking account also of the limits of the Gemini telescope, that the motion would be measurable over a period of 1-2 years.

In September 2008 the three Canadian astronomers publish their results in the Astrophysical Journal Letters.

That month, using the same technique on the same Gemini telescope, a multiple planetary system is photographed directly with 3 planets in orbit around the A-type star, HR 8799, all with masses between 7 and 10 M_{jup}. These planets have masses similar to that around 1RXS 1609, but their orbital radii are much smaller, leaving no doubt as to their planetary nature.

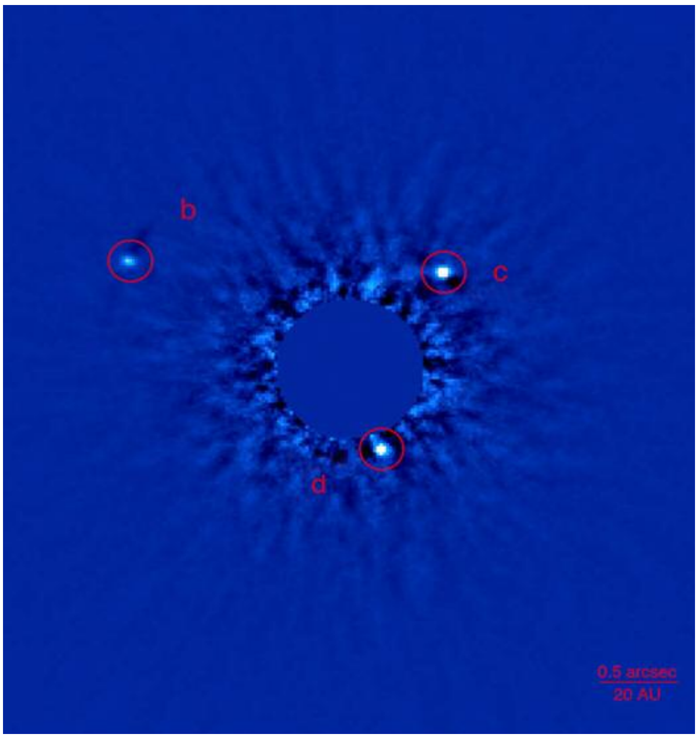
In order to regain their prize, Lafrenière and colleagues now have to prove that their object is also a planet, and already in 2009 they start to collect new images and spectra: 6th April and 1st July astrometric positions; 2nd May and 8th June 3.05 µm (H_2O) and 3.78 µm (L' band) imaging; 3rd July J-band spec-

tra. On 6th April a series of images were also taken to search for other fainter planetary bodies at smaller radii.
By the time the data were reduced it's 2010, and although the situation is already clear, it's confirmed: 1RXS J1609-2105b has the same motion as 1RXS 1609; same direction same velocity, and this is the proof that they are gravitationally connected. Also, thanks to a study carried out in 2009 by Bouy and Martin on the proper motion dispersion within the Upper Scorpius association, Lafrenière and colleagues are able to calculate the probability that the similar translational motion is a chance occurrence, ie, without a gravitational link. They find a value of 2-3 in 10,000, low enough to confirm the gravitational connection, even in the absence of a discernible orbital motion of 1RXS J1609-2105b around 1RXS 1609. Finally, via an accurate measurement of the bolometric luminosity (the total amount of electromagnetic radiation emitted at all wavelengths) the margin of error for the mass is slightly modified, being fixed at 0.008 (+0.003/-0.002) solar masses, equivalent to 8.3 (+3/-2) M_{jup}.



In 2004, and again in 2006, a candidate protoplanet was photographed in the disk around Fomalhaut (α Piscis Austrinus). In 2008 its existence was confirmed as an object that swept-up material from the disk. Neither could this object be described as the first real exo-planet photographed directly. [NASA, ESA, P. Kalas, J. Graham, E. Chiang, E. Kite, M. Clampin, M. Fitzgerald, K. Stapelfeldt, J. Krist.]

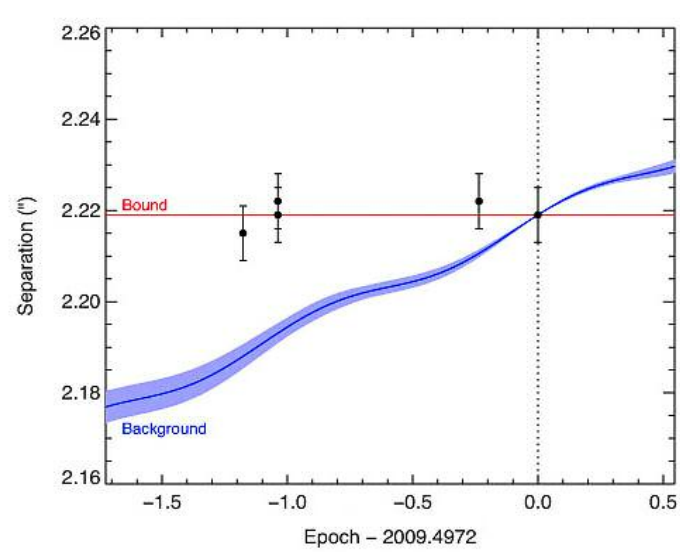
New spectroscopic observations have now confirmed the temperature and also detected potassium and iron hydride in the atmosphere.
So this object, with an infrared magnitude of around 17, visible in the Upper Scorpius association, close to a remote star 1000 times more luminous (10th magnitude) really is the first extra-solar planet to be directly photographed, and also has the largest orbit of any Jovian-sized body discovered to date.
Thanks to new data, the three astronomers were also able to exclude the presence of planets more massive than 1 M_{jup} beyond 440 AU (equivalent to a separation of 3"), 2 M_{jup} beyond 100 AU (0.7") and 8 M_{jup} beyond 50 AU (0.35"), for the 1RXS 1609 system. This does not exclude the possibility that there exist other planets that are either less massive or nearer the star, or both, but does pose a problem for the birth of this isolated planet. As mentioned above, current planet formation models don't permit the formation of 1RXS J1609-2105b at the position we see it today, and it's very large orbit can only be explained by invoking planetary orbital migration. Unfortunately, this mechanism requires the presence of several other planets of similar masses at distances from 30 to 100 AU from the star, and, as we have seen, this doesn't appear to be the case for 1RXS 1609, unless there are several planets within 50 AU. There is no evidence for this at present however.
Until the discovery of other such plan-



The first direct image of a multi-planet system, HR 8799, shown here as it appeared on 5th September 2008 in the infrared (K-band) at the Gemini Observatory. The most distant of the three detected planets is 70 AU from the star. Multi-epoch observations have made it possible to trace the Keplerian motion of the three bodies. [National Research Council Canada, Gemini Observatory]

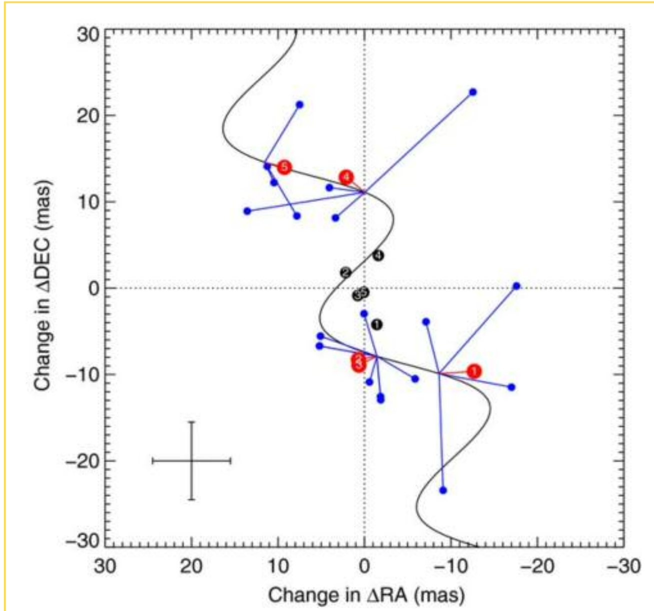
ets in the system the dynamical evolution of 1RXS 1609/1RXS J1609-2105b will remain unexplained by all the models that are based on accretion in a proto-planetary disk (too slow to build an 8 M_{jup} body at that distance in 5 million years, and unable to maintain it at the measured temperature). Other models also fail. Both those based on direct gravitational collapse of clouds of gas and dust (the preferred method for brown dwarf companions, but requires an enormous accretion disk, of which some trace should have remained), and those based on fragmentation of protostellar nuclei (rather unlikely given the small mass of the planet).

In the absence of future discoveries of massive planets at smaller radii, the only way to resolve the question (recently made more critical due to the discovery of a handful of other similar systems) is to detect the movement of 1RXS J1609-2105b in its orbit. Only in this way will we have some idea, at least, of the shape of the orbit and understand if the observed 330 AU repre-



The astrometric measurements (black points with error bars), made over a little more than a year, of the 1RXS 1609 system, show that the separation has not varied and thus that the objects are gravitationally bound. If the proximity of the planet to the star had just been a chance alignment the points would have been distributed in the blue shaded area. [Gemini Observatory, AURA, D. Lafrenière, R. Jayawardhana, and M. van Kerkwijk]

Another demonstration of the gravitational connection between 1RXS 1609 and its planet. The black circles show that the changes in separation (5 measurements) were practically zero given the error bars (cross at lower left). The blue circles are astrometric measurements of four field stars, that once averaged (red circles) lie perfectly on the curve predicted for objects not gravitationally bound to 1RXS 1609. [D. Lafrenière, R. Jayawardhana, and M. van Kerkwijk]



sent approximately the semi-major axis, or rather, due to projection effects, a random point in a much larger, perhaps very eccentric orbit. The still image tells us nothing of the direction of motion of the planet, nor exactly where it is located in space, only that we see it projected in that location. The orbit could be almost circular (which would put the models in trouble) with a period of around 6000 years, but it could also be very elliptical (for outwards migration) with minimum periods around 1000 years, and it can't even be excluded a priori that the orbit is open, and that the planet has "recently" been catapulted out of the system, however unlikely this may be.

The proper motion of 1RXS J1609-2105b that Lafrenière, Jayawardhana and van Kerkwijk expect to measure in the next few years is truly tiny, just 2.2 milliarcseconds per year (assuming that the semi-major axis is similar to the projected separation) and how many years must pass before it will be measurable depends also on the technological innovations available to astronomers.

In the meantime, higher resolution spectra will be acquired to identify other chemicals, in addition to those already detected, so as to have a more complete picture of its metallicity, helping to determine how it was formed.

A refinement of the parameters determined may further come from a precise measurement of the stellar parallax, that will reduce the error on the distance to the system, and therefore reduce the error on the mass determination.

This will show which of the current models comes closest to explaining the observed situation, giving some idea of the expected shape of the orbit.

Who would have thought there was so much to this apparently insignificant point of light!

For all the technical details we refer the reader to the article "The directly imaged planet around the young solar analog 1RXS J160929.1-210524: confirmation of common proper motion, temperature, and mass" by David Lafrenière, Ray Jayawardhana and Marten H. van Kerkwijk in the *The Astrophysical Journal* (2010), 719, 497. A preprint can be found at http://arxiv.org/abs/1006.3070.

Michele Ferrara, science writer and free thinker, after collaborating for over ten years with the Italian magazine "l'Astronomia" (as both author and editor), and realizing the crisis in which printed astronomy publications find themselves, decided to found the free astronomy webzine, l'Astrofilo, of which he is now editor in chief.