EXTRASOLAR PLANETS

Jupiter-like Planet Discovered

The observation, by high-precision spectroscopy, of a Jupiter-mass planet in a nearly circular orbit around 51 Pegasi in the left wing of the Pegasus constellation not only represents the first step on the road to identifying the first extrasolar planetary system associated with a solar-type star but also raises intriguing questions concerning the way large planets form.

The detection of planets around main-sequence stars other than the Sun represents a major astrophysical and instrumental challenge [*EN* **26** (1995) 8]. A planet orbiting around a star would be expected to reveal itself by its own emission or by a perturbation in the star's characteristics. Effects include wobbling of the star, reflection of the star's light on the planet, variation in the star's angular position (the star has a reflex motion around the common centre-of-mass of the star/planet system which leads to a variation of the star's angular position), gravitational perturbation giving a periodic modulation of the star's radial velocity, occultation and gravitational amplification of light from the star, timing of pulsar emission, intrinsic radio emission, *etc.*

By monitoring the time of arrival of signals from a pulsar, a complete planetary system consisting of two terrestial-mass planets orbiting with periods of months has been found, but at a place where nobody expected it [1]. Planets orbiting around solar-type stars rather than pulsars offer more exciting perspectives (at least to the general public), so it is understandable that the announcement on 6 October of the detection, for the first time, of a Jupiter-mass companion orbiting around a solar-type star attracted considerable attention.

Using data from the new high-precision ELOIDE fibre-fed echelle spectrograph at the Observatoire de Haute-Provence, Michel Mayor and Didier Queloz of the Geneva Observatory have reported [2] that the presence of a very low mass (0.5 Jupiter-mass) companion, called 51 Peg B, in an orbit with a semi-major axis of 0.05 Astronomical Units (AU), seems to be the most convincing explanation for the observed velocity variations of the solar-type star 51 Pegasi. Other candidate stars in a selected sample have also shown significant velocity variations over an 18-month period of observation, but they require additional measurements.

The Geneva team has monitored since April 1994 the radial velocity of a total of 142 G and K dwarf stars, this sample having been selected for its apparent constant radial velocity from a much larger sample of stars that had been monitored for 15 years at a lower sensitivity (200 m/s). The ELOIDE spectrograph, optimised for Doppler-shift studies, was used to measure the variation of the stars' positions along the line-of-sight. The sensitivity of the method means that it is currently limited to detecting velocity changes of about 15 m/s. Since the reflex motion of the Sun due to Jupiter is 13 m/s, all searches based on spectroscopy thus aim to detect companion objects which are at least as large as Jupiter.

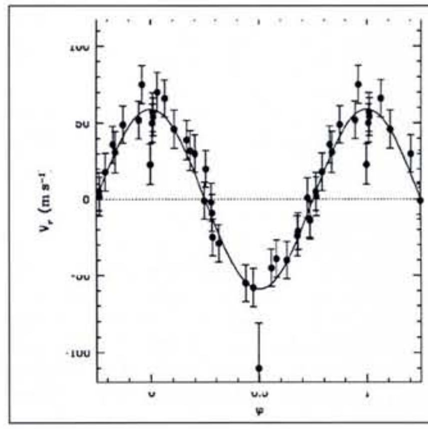
The radial velocity was computed using a cross-correlation method that concentrated the Doppler information of about 5000 stellar absorption lines. The location of a Gaussian cross-correlation function fitted to the spectral line intensities gave the radial velocity. A high accuracy was achieved owing to the scrambling effect of the optical fibre input and by continuously calibrating the instrument during exposures.

The calculated orbital motion of 51 Pegasi is plotted in the figure giving the radial velocity as a function of the phase of orbital rotation. The data have been corrected for a long-period perturbation that probably arises owing to the presence of a second companion with a small mass. Intensive monitoring of 51 Pegasi is in progress in order to confirm this long-period orbit. The solid line in the figure represents the computed motion assuming a circular orbit with a rotation period of 4.2293 ± 0.0011 days for 51 Peg B. At the present time, the eccentricity of the orbit is estimated to between 0 and about 0.15.

The remarkably sinusoidal and stable velocity curve, which favours the planet interpreation, has been confirmed independently by a joint US team from the Lick Observatory and the Harvard-Smithsonian Center for Astrophysics.

An orbital period of only 4.23 days is not too surprising for a binary star system. However, it is rather puzzling if one relates it to the relatively long orbital period of Jupiter. 51 Pegasi is a 5.5th magnitude star located 45 light years away. It is similar to the Sun, having much the same temperature and being only slightly older. Its only remarkable feature is a slightly higher abundance of heavy elements, and even this can be accounted for by the uncertainty in measuring elemental concentrations. If one assumes a random distribution of the planet-star orbital plane, there is a 1% probability that the planet is four-times the mass of Jupiter and a 2.5×10^{-5} probability that it is heavier than the minimum mass for hydrogen burning (0.8 solar masses). So one is probably dealing with a fairly low-mass companion.

This conclusion is supported by examining the rotational velocity projected onto the orbital plane. If one makes the reasonable assumption that the rotational axis of 51 Pegasi is aligned with the orbital plane, three sets of independent measurements give a projected velocity of 2.2 ± 1.0 km/s. Chromospheric activity caused by the re-emission in the core of calcium lines is related to the speed of stellar rotation *via* the magnetic field created by the dynamo effect. In the case of 51 Pegasi, the activity indicates a rotation period of 30 days so the equatorial velocity is 2.2 ± 0.8 km/s. Combining these two velocities gives an lower limit of $\sin i = 0.4$ for the inclination angle i of the orbital plane relative to the line-of-sight. Consequently the companion responsible for the 4.23-day orbit has an upper mass limit of 1.2 Jupiter-mass. If one assumes misalignment as large as 10°, the companion has still to weigh less than 2 Jupiter-mass.



The orbital motion of 51 Pegasi corrected for the long-term variation of the velocity of the centre-of-mass owing to the possible presence of a second companion of low mass. The points, plotted as a function of the phase of orbital rotation, correspond to experimental estimates of the radial velocity as determined using cross-correlation of spectroscopic data. The solid line is the theoretical curve fitted for a circular orbit with a period of 4.2293 ± 0.0011 days. It shows that the data are remarkably stable and sinusoidal.

The 30-day rotation period of 51 Pegasi is clearly not synchronized with the 4.23-day orbital period of its low-mass companion despite 51 Pegasi's very short period. This rules out the possible presence of a low-mass stellar companion since spectroscopic binaries of similar periods have been found to be synchronised in all cases. Using observed scaling laws, the lack of synchronization can in principle be used to estimate an upper limit for the mass of 51 Peg B.

The Only Convincing Explanation

Since the observed velocity variations are small and of short amplitude, it is necessary to rule out possible alternative explanations for the spectroscopic measurements. Rotation of a hot spot on the star's surface can be dismissed on the basis of the lack of chromospheric activity and the long rotation period (a solar-type star rotating with a period of 4.23 days would have a much larger chromospheric activity).

Pulsation of 51 Pegasi would be accompanied by luminosity and colour variations as well as by phase-related absorption line asymmetries. However, all-sky surveys carried out by the HIPPARCOS satellite indicate that stars with spectral features similar to those of 51 Pegasi are among the most stable. Moreover, no mechanisms have been identified which are able to excite pulsation modes as long as four days in solar-type stars. For instance, only very low amplitude (<< 1 m/s) modes and periods of minutes to one hour are detected for the Sun. Radial velocity variations of a few days and less have been observed for a few giant stars larger than 20 solar radii in size. However, 51 Pegasi is certainly not this large. Nor does it show short-period simultaneous pulsations that are characteristic of giant stars.

Photometric measurements of 51 Pegasi and of two companion stars carried out earlier this year do not completely rule out the possibility of a very low pulsation. Although stronger constraints stemming from HIPPARCOS data are expected shortly, it is noted in the meantime that pulsations are known to affect the symmetry of absorption lines. Such a feature has been sought for without success using the cross-correlation technique. So an interpretation of the observed velocity variations as being due to the orbital motion of a very low mass companion planet seems to be the most convincing.

Exciting Perspectives

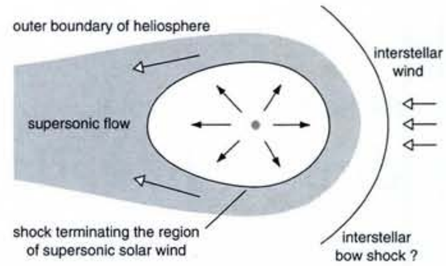
It is clear that the mass and orbital eccentricity of the 51 Peg B companion are similar to those for heavy planets. But this does not mean that the companion forms in the same way as Jupiter. Most importantly, present models do not predict the formation of Jupiter-like planets with separations as small as 0.05 AU (well within Mercury's orbit in our Solar System). It is unlikely that the accumulation of ice grains to give a Jupiter-like planet followed by orbital decay due to dynamic effects would result in a orbit as small as 0.05 AU. Secondly, all of the planets in the Solar System which are heavier than 10^{-6} solar mass have circular orbits since they grew from a protoplanetary gaseous disc. The low eccentricity of 51 Peg B does not represent evidence for a similar effect since the separation is very small. Instead, dynamical evolution of the system rather than the formation conditions may be responsible for the low eccentricity. One possibility is that 51 Peg B resulted from the radiative stripping of a nearby brown dwarf of low mass. If this is the case, it would be mostly made up of heavy elements.

Notwithstanding these more general issues, it is the possible presence of a second long-period companion to 51 Pegasi that is of the most immediate interest. If it also turns to be in the Jupiter range with a nearly circular orbit, the Geneva team will have discovered the first example of an extrasolar planetary system associated with a solar-type star.

[1] Wolszczan A., Frial, D.A., *Nature* **355** (1992) 145; Wolszczan A., *Science* **264** (1994) 538.
[2] Mayor M., Queloz, D., *Nature* **378** (1995) 355.

The Heliosphere and its Neighbourhhod

The general characteristics of the heliosphere (W. I. Axford, 1992).



The Sun's immediate neighbourhood — the heliosphere — is dominated by the solar magnetic field and the solar wind. How it is embedded in the local interstellar medium (LISM), and how these two fundamentally different media interact with each other are of fundamental importance. A dozen space missions are presently making observations both inside the heliosphere by *in situ* measurements (*e.g.*, Ulysses, exploring its three-dimensional structure, and the Voyager and Pioneer spacecraft in the outermost regions) and outside the LISM in all wavelength bands (*e.g.*, optical observations from the Hubble Space Telescope, and ultra-violet and X-ray measurements from EUVE and Rosat, respectively).

The main task of the workshop *The Heliosphere in the Local Interstellar Medium* (Bern; 6-9 November 1995) with over 40 participants from 9 countries on 3 continents — the first event to be held at the new International Space Science Institute (see insert) — was to bring together representatives of these two approaches, as well as theorists and modellers of the heliosphere, in an enviroment which would stimulate the exchange of views and data. The aim was to reach agreement on the principal parameters (such as the size of the heliosphere and the density and temperature of the LISM) and to identify points of disagreement and ways to overcome them.

Excellent agreement was reached regarding the direction and speed at which the heliosphere moves through the local cloud, as obtained from *in situ* observations of interstellar neutral gas on Ulysses and from Hubble observations of interstellar absorption lines in the spectra of bright stars. However, is now clear that accurate values can only be obtained by monitoring helium because other constituents of the LISM (in particular, hydrogen and oxygen) are affected either by deceleration and pile-up upstream of the heliopause or by deflection in front of this boundary.

Observations of interstellar hydrogen absorption lines and of the backscatter of solar Lyman-α radiation from the LISM reveal that our local cloud, which is about 1 parsec (3 x 10^{13} km) in size, may not be the home of the heliosphere much longer. Absorption spectra clearly show a second component moving at a somewhat higher speed, caused by the neighbouring G-cloud (located towards the galactic centre), into which we will move sometime during the next millennia.

The composition of the gas in our local cloud can, in principle, be determined from *in situ* observations of interstellar pick-up ions in the solar wind. However, it became apparent at the workshop that the interpretation of data needs a better understanding of ionization rates and of ion transport in the interplanetary medium. Nonetheless, the pick-up measurements confirm the view that these ions form the seed population of the anomalous cosmic-ray component, whose most prominent feature is the virtual absence of carbon. In line with this view, the recently discovered, and quite unexpected, pick-up carbon ions could be shown to stem from a local source inside the heliosphere (their three-dimensional distribution indicates that evaporating interstellar grains are the source).

The distance to the termination shock R_t where the solar wind passes from the supersonic to the subsonic regime, and to the heliopause R_h where the solar wind meets the interstellar gas, has been addressed by several different methods. Perhaps the clearest indication of R_h comes from two major radio events observed by Voyager, placing it at a distance of 110-160 astronomical units (AU). Theoretical modelling indicates $R_t = 2/3\, R_h$, putting the termination shock well within reach of the Voyager spacecraft, currently at over 60 AU and moving outward at nearly 4 AU per year. A poll among the participants resulted in a value of $R_t = 87 \pm 5$ AU, which means that Voyager ought to reach the boundary of our heliosphere within the next decade. The result may, however, be biased to a low value owing to the participants' hope that they will be alive to witness this historic event.

International Space Science Institute

The International Space Science Institute (ISSI) was formally inaugurated on November 10, several months after opening its doors to collaborators. Modelled on advanced studies institutes, the ISSI aims to enable space scientists involved in today's many space missions to pool data and understanding in order to interpret scientific results in a broad, interdisciplinary context while not overlooking the results of ground- and laboratory-based research. J. Geiss, the ISSI Executive Director and a prime instigator behind the initiative, thinks that the new institute will be able to "bring out an integrating view" to studies that encompass many aspects. This approach clearly struck home to delegations to the Inter-Agency Consultative Group (IACG) from the European Space Agency (ESA), NASA, Japan's Institute of Space and Astronautical Studies (ISAS), and the Russian Academy of Sciences when the IACG endorsed the ISSI's scope in 1994. In the 1980's, these national agencies mandated the IACG to coordinate missions to Halley's Comet and programmes in solar-terrestrial physics because