Three planets for Upsilon Andromedae

Jack J. Lissauer

In 1997, a planet of roughly Jupiter's mass was discovered in orbit around the star υ Andromedae. Two more have now been identified.

In the 1990s, the quest to find planets outside our own Solar System finally succeeded. The first extrasolar planets to be identified are in orbit around a pulsar¹, a rapidly rotating neutron star which is quite different from our own familiar Sun. The first planetary companion to a main-sequence star — a hydrogen-burning star like the Sun — was discovered in 1995, using Doppler measurements of the reflex motion (wobble) that the planet's orbit induces in the star 51 Pegasi². Nearly 20 more main-sequence stars have since been found to possess a single companion of roughly Jupiter mass³. But now we have news of something else again — the discovery, announced last week by Paul Butler and his colleagues⁴, of a system of three massive planets orbiting the star υ Andromedae.

All of the planets known to orbit main-sequence stars other than the Sun have been identified using the Doppler technique, which measures changes in the star's velocity component along the line of sight. These observations can be inferred as perturbation of the star by a companion planet. They yield the planet's orbital period and orbital eccentricity, and the product of its mass and the sine of the inclination of its orbital plane to the plane of the sky, $M\sin(i)$. Because $\sin(i)$ cannot exceed unity, the measured radial-velocity variations of the star provide a lower limit to the planet's mass.

Determining the masses and orbits of three planets travelling about a star using Doppler data is a highly complicated business, because the data have significant intrinsic scatter and the signatures of the planets interfere with one another. Butler *et al.*⁴ looked at two sets of data, obtained respectively at the Lick Observatory in California and by the Advanced Fibre-Optic Echelle (AFOE) spectrometer at the Whipple Telescope in Arizona. They analysed these data independently, and when combined, to derive three sets of planetary parameters. The similarity of the values of these parameters (see Fig. 1) lends confidence to the three-planet solution.

The star υ Andromedae has a mass about 30% greater than that of our Sun, is about halfway through its six-billion-year main-sequence lifetime and is about 44 light years from our Solar System. The innermost planet was first discovered in 1997 (ref. 5). It has a nearly circular orbit with a period of 4.6 days,

and a minimum mass about 0.7 times that of Jupiter; these properties are similar to those of the only known planet of 51 Pegasi and to other star-grazing planets.

What about the two newcomers identified by Butler *et al.*? The middle planet has a period of about 242 days, a mass about twice that of Jupiter and an orbital eccentricity, e , of approximately 0.22 (comparable to the eccentricities of Mercury and Pluto, and larger than the orbital eccentricities of all other planets known in our Solar System). The orbital period of the outer planet is $\sim 1,270$ days; $e \sim 0.36$; and mass ~ 4.1 times that of Jupiter. These latter values are not well constrained, because most of the Doppler data were taken within a 6.5-year interval, less than two orbital periods of the planet. But the masses and eccentricities of the outer

two bodies are typical of half-a-dozen known extrasolar giant planets with orbital periods of around a year.

Additional constraints on the υ Andromedae planets come from astrometric and photometric data, as well as from numerical orbit integrations. The Hipparcos astrometric satellite observed the position of υ Andromedae on the plane of the sky several times during the early 1990s. No wobble is detectable in these data, which implies that the outermost planet is less than ten and probably no more than five Jupiter masses. Photometric measurements of the brightness of υ Andromedae around the times that the inner planet would pass in front of (transit) the star if its orbital plane were nearly along the line of sight ($\sin(i)$ close to 1) rule out transits deeper than about 0.0002 to 0.0003 magnitude (G. W. Henry, personal communication). This means that the inclination of the planetary orbit must be less than 83° or that we are dealing with an extremely dense, exotic object.

As far as numerical integrations are concerned, the preliminary results of calculations by myself and a colleague, E. J. Rivera, imply that a system having the parameters derived from the AFOE data only, with $\sin(i)$ of approximately 1, would tear itself apart within a million years or so (Fig. 1). (The chaotic nature of such a trajectory precludes

Figure 1 The reported orbital parameters for the planets around υ Andromedae⁴ are given on the left side of the plot. The orbit of each planet is represented by three points — the periastron and apoastron (closest and farthest distances from the star, bottom and top points) and the semimajor axis (roughly, the average orbital distance). Triangles represent the outer planet, crosses the middle planet and circles the inner planet. Error bars are shown for the outer two planets; observational uncertainty is far less for the innermost planet. Data from the Lick Observatory are given in green and from the AFOE (Whipple Telescope) in red; combined data are in black. The rest of the plot shows the temporal evolution of the periastra and apostra of the three planets using the nominal parameters on the left as initial conditions. The systems using the combined and Lick data sets continue to be stable for the entire ten-million-year integration interval. (Calculations and figure by E. J. Rivera of SUNY, Stony Brook, and J.J.L. using the SwIFT symplectic MVS package⁸.)

a precise calculation.) The star, and thus presumably its planets, are about three billion years old, and it would be extremely unlikely that the system just happens to be so near to the end of its expected lifetime. What the calculation implies, then, is that the nominal AFOE parameters are unlikely to be correct. Nonetheless, the characteristics of the system could well be within the error bars quoted for the AFOE data.

By contrast, systems using the Lick or combined Lick/AFOE data sets appear to be stable for at least ten million years and possibly much longer. Additional integrations, not shown in Fig. 1, imply that systems with more massive planets (smaller $\sin(i)$) are generally less stable, especially if the orbits are substantially inclined to one another, and that changing the orbital period of the outer planet within the range allowed by the data can have a big effect on the stability of the system.

Neither the star ν Andromedae nor any of its three planets appear in themselves to be particularly unusual, but the system as a whole stands out in the currently known menagerie of extrasolar planets. Its existence shows that several massive planets can orbit far closer to a star than do the gas giants (Jupiter and Saturn) and smaller ice giants (Uranus and Neptune) of our Solar System. So if giant planets all form far enough out in a protoplanetary disk for ice to condense (the conventional, but not exclusive, view of theorists⁶), then the migration or mutual scattering (or both) that brings them in towards their star is not always violent enough to

destroy themselves or their brethren.

The ν Andromedae system is just one example of a wide variety of planetary configurations that can be expected to exist in our Galaxy. All of the extrasolar planets thus far discovered orbiting main-sequence stars are more massive than Saturn, and most either orbit very close to their stars or travel on much more eccentric paths than do any of the major planets in our Solar System. The Sun's planets are all either low in mass or travel on distant orbits from their star, and they are therefore more difficult to discover using the Doppler technique. So it could be that most planetary systems will turn out to be like ours.

There is much, much more to come. With the projected advances in detection technology, including schemes to find Earth-like planets⁷, we are at the beginning of a Golden Age of extrasolar planetary studies. □

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ions of the salt and the molecular pore in the α -haemolysin channel. When a bias is applied across the membrane, the current flow is tiny (at the picoampere level), but it can nonetheless be measured with modern room-temperature semiconductor electronics.

The innovative step here¹ is to sensitize the nanopore to specific organic chemical species by using β -cyclodextrin as an adapter. β -cyclodextrin, a doughnut-like molecule made of seven sugar units, diffuses into the α -haemolysin channel, partially obstructing its water-filled pore. The authors show that the cyclodextrin molecule is exquisitely sensitive to different guest molecules. Thus, when bound to cyclodextrin, members of the adamantane family of petroleum derivatives can be distinguished, as can members of the group of tricyclic pharmaceuticals that include imipramine and promethazine. These guest molecules each bind to β -cyclodextrin for milliseconds and make their presence known by altering the electrical conductivity of the α -haemolysin pore in which the β -cyclodextrin resides.

In neurobiology and biophysics, it is routine to measure picoampere ionic currents passing through single protein channels in biological membranes or planar lipid bilayers³. Such measurements are usually made to determine the properties and behaviour of the channel, but they can also reveal details about the concentration and other properties of molecules that are able to pass through or into the channel. Very small alterations in the distribution of charges lining the pore can give rise to relatively large changes in the ionic flux, so a membrane channel can serve as an amplifying transducer. Such a transducer allows one to detect extremely small modulations ($<0.02 kT$) in the energy barrier to ionic transport⁴, and does so at bandwidths that permit high-speed ($<50 \mu\text{sec}$) measurements. Thus, membrane channels have been used to effect high-speed molecular counting and sizing^{5,6}, and show promise for high-speed sequencing of polynucleotides⁷. Channels have also been modified to incorporate design elements that convert them into sensitive, analyte-driven switches⁸, or genetically engineered to create selective, divalent metal sensors⁹.

Bayley and his colleagues have long puzzled over how to engineer or redesign the α -haemolysin channel as a biosensor that can discriminate between different organic molecules⁹. They reasoned that the sensitivity and extraordinarily rich informational content of single-channel recordings reduce the requirement for the channel to contain a highly selective binding site. By fashioning a single-channel detector, rather than one that integrates signals from numerous sensor molecules, several independent

Biochemical sensors

Adapting to nanoscale events

Daniel Branton and Jene Golovchenko

A hallmark of twentieth-century science has been the continual development of experimental strategies to observe individual atomic-scale 'events'. These strategies ultimately rely on significantly amplifying the consequences of a selective microscopic interaction, for example the chemical development of a silver halide grain in a photographic emulsion, the condensation of a droplet around a single ion in a cloud chamber, or the charge amplification in electron multiplier devices.

New strategies for detecting and characterizing single-molecule events are now emerging in the biochemical sciences. The latest example comes from Gu *et al.* on page 686 of this issue¹. This group, working in Hagan Bayley's laboratory, show how measurement of ionic transport through a single, atomic-scale pore in an insulating membrane can be used to detect organic molecules of relative molecular mass as low as 100. Coupled with highly sensitive semi-

conductor electronics, the membrane-pore system can amplify these currents on timescales commensurate with the interaction times between the molecule and the pore. The system thus reveals the presence, nature and interaction of single molecules with the pore. Remarkably, a single protein channel can be adapted for simultaneous analysis of a mixture of organic molecules.

Gu *et al.*¹ assemble the nanoscale chemical and mechanical building blocks of their detector from the toolbox of biochemistry; the key components are shown in Figs 1 and 2 of the paper on page 687. Seven α -haemolysin molecules (a bacterial toxin) self-assemble to form a channel with a 15-Å-diameter aqueous pore through a 50-Å-thick lipid bilayer membrane². The membrane separates two chambers filled with a conducting salt solution. Because the lipid bilayer is a nearly perfect insulator, the d.c. electrical conductance across the membrane is determined by the interaction between