produced by γ-ray photon-photon scattering in a hot, dense accretion disk from which some positrons escape to annihilate in surrounding gas clouds. Variability arises from changes in the accretion rate. The high-mass models incorporate rotating black-hole dynamos that electrodynamically generate beams of $e^- - e^+$ pairs and γ-rays along the rotation axis. The interaction of the emitted beam with a moving cloud produces the annihilation radiation and provides a mechanism for variability. A high-mass black hole must necessarily be at the dynamical centre of the Galaxy, whereas a low-mass black hole need not.

Recently, a tentative identification of the positron source with the X-ray pulsar GX1 + 4 was suggested[24], based on the similarity of the X-ray and γ-ray light curves over 18 years, the positional agreement of the sources (galactic longitude $l^{II} = 1.9°$, latitude $b^{II} = 4.8°$) and the unusual properties of GX1 + 4. Although no modelling of GX1 + 4 (a magnetized neutron star with an M6III red-giant companion) as a positron source has yet been published, it is natural to think that a version of the accretion-driven dynamo mechanism proposed[25] for some low-mass X-ray binaries may be applicable here. Such a dynamo could electrodynamically produce the required number of positrons. The variability might arise either from an eclipse of the positron source[24] (the orbital period of GX1 + 4 is unknown) or from an episodic ejection of mass from the M giant, smothering the X-ray source[26]. The GRIS data are being searched for the characteristic 2-min pulsation period of such a source.

It is therefore desirable to locate the γ-ray object using imaging and scanning techniques and to frequently monitor the X-ray/γ-ray flux with the GRO/OSSE[27] and GRANAT/SIGMA[28] detectors, with balloon instruments such as GRIS, and with the Ge spectrometer on the proposed Nuclear Astrophysics Explorer mission[29]. ☐

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The unseen companion of HD114762: a probable brown dwarf

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BROWN dwarfs are substellar objects with too little mass to ignite hydrogen in their cores. Despite considerable effort to detect brown dwarfs astrometrically[1–4], photometrically[4–9], and spectroscopically[10–12], only a few good candidates have been discovered. Here we present spectroscopic evidence for a probable brown-dwarf companion to the solar-type star HD114762. This star undergoes periodic variations in radial velocity which we attribute to orbital motion resulting from the presence of an unseen companion. The rather short period of 84 days places the companion in an orbit similar to that of Mercury around the Sun, whereas the rather low velocity amplitude of about 0.6 km s^{-1} implies that the mass of the companion may be as low as 0.011 solar masses, or 11 Jupiter masses. This leads to the suggestion that the companion is probably a brown dwarf, and may even be a giant planet. However, because the inclination of the orbit to the line of sight is unknown, the mass of the companion may be considerably larger than this lower limit.

For more than ten years we have been monitoring carefully the radial velocities of a few dozen stars with the goal of establishing an improved set of velocity standards for the International Astronomical Union[13]. Two different instrument systems have been used: digital speedometers operated by the Center for Astrophysics (CfA) at the Oak Ridge and Whipple observatories[14], and CORAVEL spectrometers at the Haute-Provence and ESO-La Silla observatories[15]. One of these standard stars is HD114762 (= BD + 18°2700 = SAO100458; RA = 13:09:54.53, dec. = + 17:46:55.4 [1950], $V = 7.3$). With a $B-V$ colour of 0.53 and surface temperature of about 5,800 K, it closely resembles the Sun, except for a lower abundance of chemical elements heavier than helium, by 0.8 dex (where 0.8 dex = $10^{0.8}$, dex being the interval in powers of 10) (ref. 16). The star has a high proper motion and was therefore included in the survey of Carney and Latham[17], who determine a photometric distance of 28 pc (about 90 light years).

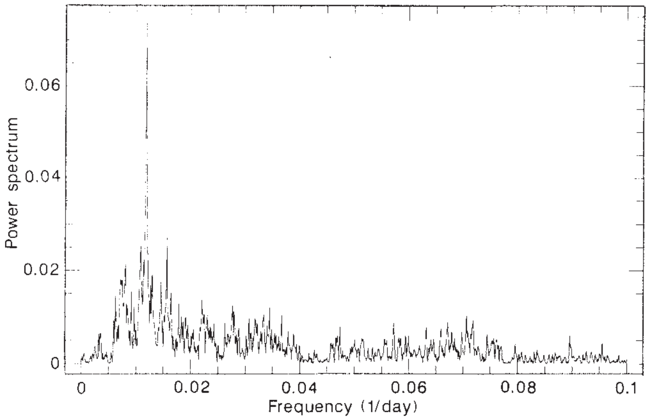

FIG. 1 The power spectrum in relative units for all 280 velocity observations of HD114762 in the combined CfA and CORAVEL data set.

On 1 April 1988, during test observations with a new fibre feed for the digital speedometer at the Oak Ridge Observatory[18], we noticed a possible variation of HD114762. An examination of the 63 observations taken over the preceding seven years disclosed a periodic variation, with a period of 84 days. The periodicity was subsequently confirmed by the independent CORAVEL data and by extensive additional observations obtained with the CfA speedometers. The power spectrum[19] for the full combined data set of 280 measurements is shown in Fig. 1. The prominent peak dominating Fig. 1 corresponds to a period of 84.02 ± 0.1 days for a pure sine function with half amplitude of about 0.5 km s^{-1}. Even though the error in each individual velocity observation, typically 0.4 km s^{-1}, is similar to the derived amplitude, Fig. 1 leaves no doubt that the data include a periodic modulation.

Are there astrophysical phenomena, besides orbital motion, which might mimic the small periodic velocity modulation found for HD114762? Simple pulsation can be ruled out; given the observed velocity amplitude and period, the star would approximately double its radius by such pulsations. The corresponding light variations would be larger than the upper limit inferred from the available photometry. For example, the fourth edition of the Geneva Catalogue[20] lists 24 *V* measurements of HD114762 distributed in phase over the 84-day period, with an r.m.s. amplitude of about 0.006 mag.

Another source of apparent velocity shifts in stellar lines at the level of a few tens of m s^{-1} might be atmospheric circulations or surface activity such as spots combined with stellar rotation. However, such phenomena cannot produce strictly periodic phenomena lasting over many cycles with amplitudes as large as a few hundred m s^{-1} in an old dwarf star[21]. Thus we suggest that the velocity variations seen in HD114762 must be due to orbital motion induced by an unseen companion.

Table 1 lists the parameters of our orbital solutions based on the CfA data alone, CORAVEL data alone, and the full combined data set, derived using our own computer codes with equal weight assigned to each observed velocity. The good agreement indicates that our orbital solutions are robust. Note that no adjustment to the velocity zero points was required when combining the CfA and CORAVEL data. In Fig. 2 we plot the orbital solution for the full combined data set, together with the individual observed velocities.

TABLE 1 Orbital solutions

	CfA	CORAVEL	Combined
Period (days)	.84.03 ± 0.14	83.91 ± 0.09	84.05 ± 0.08
System velocity, γ (km s^{-1})	49.31 ± 0.03	49.39 ± 0.06	49.35 ± 0.04
Orbital half-amplitude, K (km s^{-1})	0.55 ± 0.04	0.75 ± 0.12	0.57 ± 0.04
Eccentricity, e	0.26 ± 0.07	0.30 ± 0.15	0.25 ± 0.06
Longitude of periastron, ω (°)	237 ± 11	280 ± 16	235 ± 10
Epoch, T (Julian date − 2440000)	5,029 ± 5	5,033 ± 4	5,027 ± 4
Mass function (10^{-6} $M_\odot$)	1.3 ± 0.3	3.1 ± 1.5	1.4 ± 0.3
Number of observations	230	50	280
r.m.s. residuals (km s^{-1})	0.42	0.39	0.42

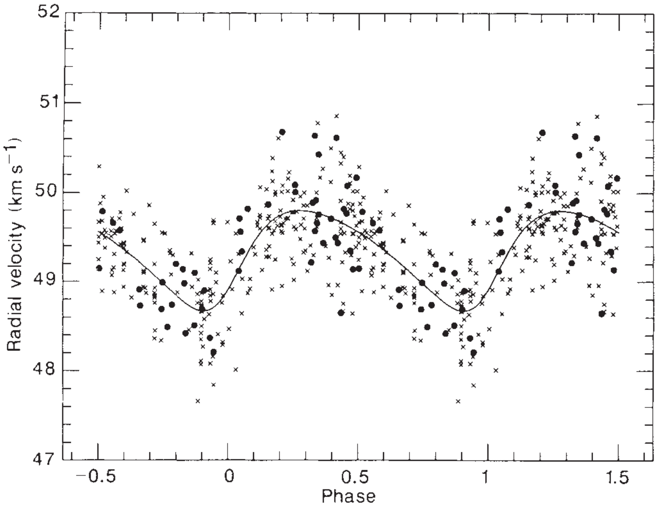

FIG. 2 The orbital solution for the combined data set. The continuous line is the orbital solution with the parameters of Table 1. The CfA velocities are denoted by crosses, the CORAVEL velocities by filled circles.

For a spectroscopic binary with a primary of mass M_s, an unseen companion of mass M_c, and an orbital plane inclined to our line of sight with an angle *i*, the mass function can be approximated by $(M_c \sin i)^3/M_s^2$, if M_c is much smaller than M_s. For HD114762 this leads to

$$M_c \sin i = 0.011 \pm 0.001\ M_\odot$$

where we have used the fact that $M_s \approx M_\odot$. This value of M_c is much smaller than 0.08 $M_\odot$, the traditional dividing line between brown dwarfs and stable hydrogen-burning stars[22-25]. Actually, this value is even smaller than 0.02 $M_\odot$, the proposed dividing line between a brown dwarf companion (formed by fragmentation) and a planetary companion (formed by accretion in a cold disk of material around the star)[26]. Thus the unseen companion of HD114762 is a good candidate to be a brown dwarf or even a giant planet. However, we cannot be certain of the mass of the companion, because we do not know sin *i*. The probability of an orbit having inclination *i* is proportional to sin *i*, if the sample is unbiased and the orbits are orientated randomly. For the companion of HD114762 to be massive enough to burn hydrogen stably, the orbit would have to be within 8° of being viewed face-on, which has a probability of less than 1%.

Finding the orbital inclination of this system is clearly of great importance. In principle this might be done by determining the astrometric orbit, as has been accomplished recently in the case of Gliese 623 (ref. 11). However, the displacement expected for HD114762 is less than 10^{-3} arcsec, too small to be detected in the near future. Another way to pin down the orbital inclination would be to observe eclipses of HD114762 by its unseen companion. Because an eclipse could occur only for an orbit viewed within half a degree of being edge-on, this possibility is rather unlikely. Nevertheless, eclipses should be looked for, as they might allow determinations of the size and temperature of the companion, as well as its mass.

How many low-mass companions are there in the solar neighbourhood? Although we consider answers based on a single example to be unsatisfactory, nevertheless it is illuminating to consider how many other stars have had their velocities scrutinized as carefully as HD114762. The number is of the order of 50, if we consider the stars that have been observed intensively as candidates for new IAU radial-velocity standard stars[13]. HD114762 is the only one of these to have so far shown an unquestionable low-amplitude periodic modulation. However, a few other of these stars also show small velocity variations which may yield convincing orbital solutions in the future. We also note that one of the four well observed giant stars which were chosen to serve as the fundamental standards for the Cambridge radial-velocity spectrometer, HR152, was subsequently shown to have a spectroscopic orbit[27]. With a period of 576 days and an amplitude of 0.69 km s^{-1}, the mass of the companion would be 35 Jupiter masses for an orbit viewed edge-on. Thus, brown-dwarf companions might not be as rare as suggested by Campbell *et al.*[10] and by Marcy and Benitz[12], based on their studies of 18 and 70 stars respectively. To learn more about the frequency and characteristics of low-mass companions, we need the results from surveys to monitor the radial velocities of large samples of stars with well-defined selection criteria.

Despite considerable efforts to detect planetary systems around other stars, the Solar System itself is the only certain example that we have. Although the detection of a planet as small as the Earth around another star by spectroscopic techniques will be difficult, the discovery of low-mass companions around other stars by this and other techniques[28] is an important step towards understanding the frequency with which planets and planetary systems occur. ☐

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Primordial binaries and globular cluster evolution

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MANY of the globular clusters in our Galaxy have probably undergone core collapse, and are currently re-expanding[1,2]. This re-expansion requires a central energy source. Previously proposed mechanisms are either inefficient or may produce unacceptably bright cores[3]. Here we explore the most conservative solution to this problem. We suggest that primordial binaries, for which there is now direct evidence[4–6], could provide the necessary energy. We show that this mechanism leads to relatively large core sizes, containing ~1% of the total cluster mass. Such a cluster would have a resolvable core (with a size of the order of arcseconds) which would consist mostly of binaries.

Globular clusters are known to undergo core collapse, driven by two-body relaxation which conducts heat from the centre to the outskirts[7,8]. For a system composed of point masses (without binaries) this process formally produces infinite density in a few half-mass relaxation times $t_{\rm rh}$ (ref. 9). The median value is $t_{\rm rh} \approx 2\times 10^9$ yr, which suggests that many globular clusters have already collapsed[9]. Indeed, the observed fraction of clusters with unresolved cores[1] is ~20%.

Before infinite density is reached, other physical mechanisms will halt the collapse, then causing the cluster as a whole to expand on a timescale of $\sim 10 t_{\rm rh}$ (refs 3,10). The core adjusts itself to supply the required energy, in much the same way that the nuclear energy sources in the Sun are regulated by energy loss from the photosphere[2]. Thus the time-averaged energy generation rate in the core is independent of the mechanism. The more efficient the energy generation mechanism, the lower is the central density and the larger is the core radius. The mechanisms responsible for core 'bounce' and for post-collapse expansion need not be the same.

If a globular cluster can be considered as a system of point masses, energy is produced by binaries formed in three-body encounters and by subsequent interactions of these binaries with single stars[11-13]. This mechanism is, however, very inefficient, and requires extremely small, dense cores both at core bounce and in post-collapse[14]. Because of the finite radii of non-degenerate stars, however, $\sim 10^3$ binaries will form by tidal capture before the bounce[15]. As these binaries are nearly in contact, subsequent interactions with single stars are likely to lead to mergers (refs 16, 17 and P. W. Cleary and J. J. Monaghan, preprint). Because of their higher mass, stars produced in such mergers evolve rapidly, and then shed mass in the form of stellar winds which escape the core or even the cluster. By diminishing the binding energy of the core, this process indirectly supplies energy to the cluster. The required mass loss rate is ~1% of the total cluster mass every $t_{\rm rh}$ (refs 3, 10, 15). If this mass loss rate is associated with normal stellar evolution, the optical luminosity of the (small) core is comparable to that of the whole cluster, in contradiction with the observation[3].

There are several ways out of this problem. Merging of main-sequence stars with white dwarfs or neutron stars may cause significant instantaneous mass ejection[18]. Alternatively, the cluster could contain an extremely dense core of compact objects, which generate energy by three-body formation of binaries[19]; but the energy production by tidal binary formation and mergers with normal stars will still be appreciable[19]. A black hole of mass $\lesssim 10^3\, M_\odot$ would liberate binding energy by swallowing stars[20] and would support a large core, but it is not clear how such a black hole could form in a globular cluster.

A more conservative solution to the problem is to assume a modest population of primordial binaries. Recent radial-velocity surveys demonstrate that >1% of all giant stars in globular clusters are members of binaries, and suggest a total binary population of >10% by mass[4]. Previous work has shown that primordial binaries are ineffective in halting core collapse[21]; their importance in powering post-collapse expansion, however, has scarcely been considered.

The energy production rate per unit volume is

$$\varepsilon = \left[\, f A_{\rm bs} n_{\rm s} n_{\rm b} + \tfrac{1}{2} f^2 A_{\rm bb} n_{\rm b}^2 + 2f(1-f) A_{\rm bs} n_{\rm b}^2 \right] \frac{G^2 m^3}{v_{\rm s}} \qquad (1)$$

where $n_{\rm s}$ and $n_{\rm b}$ are the number densities of single and double stars; m is a typical mass of a single star; $v_{\rm s}$ is the one-dimensional velocity dispersion of single stars; f is the fraction