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LETTER

Letter to the Editor

Accurate masses of very low mass stars⋆,⋆⋆

II. The very low mass triple system Gl 866

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Abstract. We present very accurate orbital parameters and mass measurements (2.4% accuracy) for the well known very low mass triple system Gl 866. We obtain first orbital elements for the short-period orbit and greatly improve the long period orbit. All three stars have masses close to 0.1 $M_{\odot}$, and the system thus provides the strongest constraints to date on the mass-luminosity relation close to the brown dwarf limit.

Key words: stars: binaries: general – stars: binaries: spectroscopic – stars: binaries: visual – stars: low-mass, brown dwarfs – stars: late-type

1. Introduction

The nearby multiple system Gl 866 has attracted considerable attention over the last decade, as it comprises some of the coolest dwarfs for which dynamic masses have been measured. At d=3.45 pc (Van Altena et al. 1995) the Gl 866 system (α=22:38:34; δ=-15:18:02; eq=2000.0) is a very close neighbour of ours, with an M5.5V joint spectral type (Henry et al. 1994). Leinert et al. (1986) and McCarthy et al. (1987) independently discovered it to be a binary from IR 1-D speckle observations, as well as Blazit et al. (1987) from visible speckle observations. Leinert et al. (1990) first determined the elements of the orbit (P=2.2 years) from three years of speckle observations, and Heintz (1993) used astrometric measurements to improve the period to P=2.27 years. Leinert et al. (1990) derived an accurate (∼5%) total mass for the system, which however was too large for the measured luminosities. For the last few years, and at least amongst very low mass star observers, it has been common knowledge that the brighter component of the 0.35″ pair is itself a short period binary (Gl 866 AC), though we could not trace when this was first mentioned in the literature. This resolves the mass discrepancy identified by Leinert et al. (1990).

In this letter we present new radial velocity and angular separation measurements, which we use to determine substantially improved elements for the outer orbit, together with first orbital elements for the inner one. We then proceed to briefly discuss the mass-luminosity relation for the bottom of the main sequence, in the light of the derived masses.

2. Observations and data analysis

Radial velocity measurements were obtained with the ELODIE spectrograph (Baranne et al. 1996) on the 1.93m telescope of the Observatoire de Haute Provence (France) between September 1995 and July 1999. This fixed configuration dual-fiber-fed echelle spectrograph covers in a single exposure the 390–680 nm spectral range, at an average resolving power of 42000. The spectra were analysed by numerical cross-correlation with an M4V one-bit (i.e. 0/1) mask, as described by Delfosse et al. (1999a). With this setup Gl 866 is a clear triple-lined system, with relative depths for the three well separated correlation peaks of ∼7, ∼6 and ∼1% (Fig. 1). The individual radial velocities have typical accuracies of 50–80 $\mathrm{m.s^{-1}}$ for the two brighter components and 200–500 $\mathrm{m.s^{-1}}$ for the fainter one.

Our orbital analysis largely relies on the numerous speckle measurements of the Gl 866 system obtained by Leinert et al. (1990). We have also obtained one angular separation measurement at the 3.6-m Canada-France-Hawaii Telescope (CFHT) with the PUE'O Adaptive Optics Bonnette (Rigaut et al. 1998) and the KIR infrared camera (Doyon et al. 1998): $\rho = 0.200{\pm}0.001''$ and $\theta = 204.1{\pm}0.9^{\circ}$ on July 23rd 1998 (JD = 2451018). Delfosse et al. (1999a) provide a detailed description of the observing and analysis procedure, which we don't repeat here. As the maximum separation between components A and C is ∼0.010″ (Sect. 3), all separation observations

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⋆ Based on observations made at the Observatoire de Haute Provence (CNRS), and at the CFH Telescope, operated by the NRCC, the CNRS and the University of Hawaii

⋆⋆ Table 3 is only avaliable electronically with the On-Line publication at http://link.springer.de/link/service/journals/00230/

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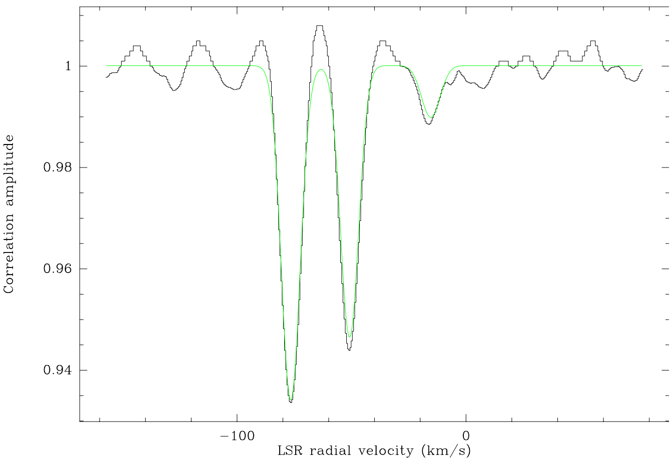

Fig. 1. The ELODIE correlation profile on Julian day 2450389.3191 (a well separated configuration of the three peaks), and its adjustment by ORBIT.

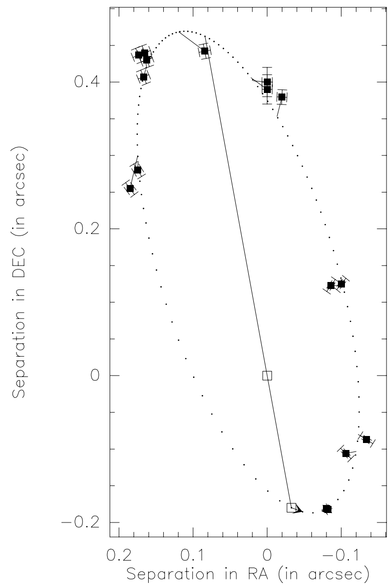

Fig. 2. Visual outer orbit.

to date, whether speckle, adaptive optics or with HST (Henry et al. 1999), only resolve the AC photocenter from the B components.

We have used the ORBIT program (Forveille et al. 1999) to determine the elements of both orbits through a least square adjustment to all available observations, including the trigonometric parallax of 0.2943″±0.0035″ (Van Altena et al. 1995). ORBIT directly supports triple systems (as well as symetrical quadruples), as long as three-body effects can be neglected. We have not used the individual velocities but instead made use of a recent improvement to ORBIT (see Forveille et al. 1999 for details) to directly adjust the orbits to the cross-correlation profiles. This direct adjustment to the profiles significantly improves the accuracy of the orbital parameters, by greatly decreasing the effective number of free parameters of the adjustment. This gain is particularly important for Gl 866, whose three correlation peaks blend for many velocity configurations, and whose weaker C component is sometimes only detected with a low signal-to-noise ratio.

This adjustment directly produces orbital elements, without intermediate radial velocity that we could make available. The radial velocity (available in the electronic form of this paper) were obtained by classical Gaussian fits to the individual correlation dips, but we recommand that reanalyses of our data directly use the raw correlation profiles, which we will make available upon request.

3. Orbital elements and masses of Gl 866

Fig. 3 and Table 2 together summarize the orbital solution which results from this simultaneous adjustment of both orbits to the radial velocity, angular separation, and parallax data. The brightest and most massive component of the system (A) and its faintest and lightest one (C) constitute a close binary with a ∼ 3.8 day period, orbiting with the third star (B) in a 823 day orbit. With P_{out}/P_{in}∼200, the system is strongly hierarchical. This justifies our use of two non-interacting keplerian orbits in the adjustment, which amounts to neglecting all second order gravitational effects. As just an example, the expected nodal precession period for the parameters of Gl 866 is $T_{prec} \sim 900$ years (Harrington 1968, Mazeh and Saham 1976), very much longer than the 4 year span of the radial velocity observations (we argue below that the system is probably coplanar, so that nodal precession in particular probably has a small or null amplitude, in addition to this long period). We find no secular trend in the residuals, also vindicating the use of two keplerian orbits. Most orbital elements are essentially constrained by the spectroscopic data alone, except for the semi-major axis, the inclination (i) and the orientation of the nodal line on sky (Ω), which are only constrained by the angular separation data and the parallax.

Table 1. Derived physical parameters.

	Masses	
M_A (in $M_\odot$)	0.1216	± 0.0029
M_B (in $M_\odot$)	0.1161	± 0.0029
M_C (in $M_\odot$)	0.0957	± 0.0023
	Outer Orbit (AC-B)	Inner Orbit (A-C)
a1 (in a.u.)	0.775	0.012
a2 (in a.u.)	0.414	0.016
orbital parallaxe	290.4 ± 2.7 mas	

The inner orbit has negligible eccentricity, as expected from tidal circularisation for its short period. The physical separation between A and C is only 0.03 a.u. (Table 1), but, thanks to the small distance to Gl 866, their apparent separation is ∼0.01″. Infrared interferometers with baselines longer than ∼40m (such as the future VLTI) will be able to resolve this pair, which is also an excellent target for observations as an astrometric binary: the large mass ratio and ∼2 mag V band magnitude difference combine to produce a ∼±0.005″ astrometric amplitude in the passband of the FGS astrometers on *HST*, well within the range

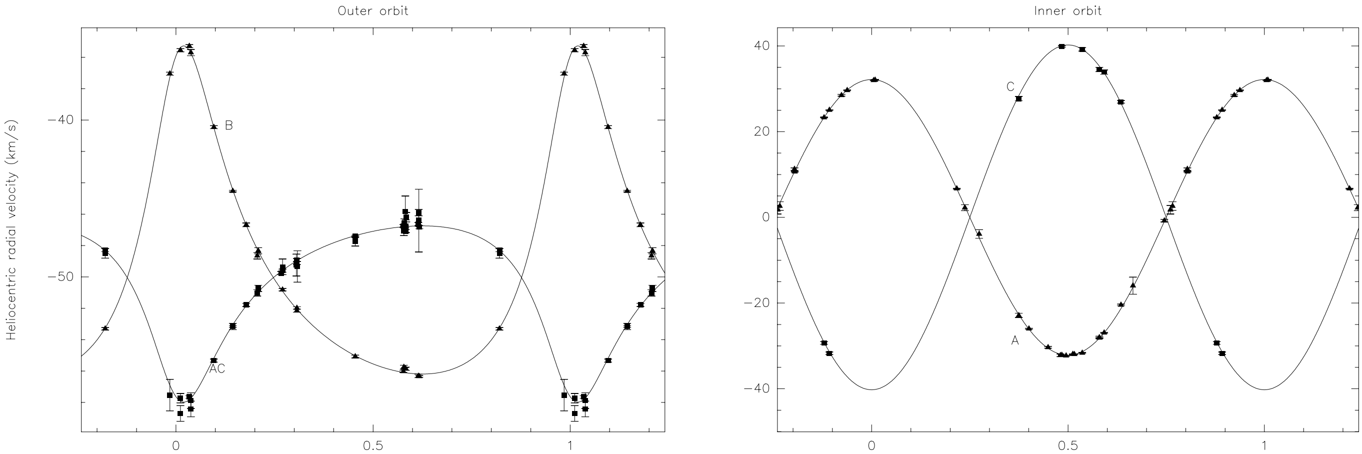

Fig. 3. Phased radial velocity curves for the outer and inner orbits of Gl866. In both cases the contribution of the other orbit has been subtracted from the displayed measurements.

Table 2. Orbital elements of the outer (AC-B) and inner (A-C) orbits of Gl 866.

	P (days)	T_0 (Julian day)	e	a (arcsec)	i (deg)	Ω (deg)	ω (deg)	K_1 ($\mathrm{km\,s^{-1}}$)	K_2 ($\mathrm{km\,s^{-1}}$)
Leinert et al. (1990)	803.5		0.41	0.36	112	163	340		
(Outer Orbit (AC-B))	± 8		± 0.01	± 0.01	± 2	± 2	± 5		
This letter	822.6	48517	0.446	0.346	112	161.5	337.6	10.62	5.64
(Outer Orbit (AC-B))	± 0.6	± 2.5	± 0.003	± 0.002	± 1	± 0.6	± 0.6	± 0.06	± 0.04
This letter	3.78652	50640.775	0.000		∼ 117			32.11	40.8
(Inner Orbit (A-C))	± 0.00001	± 0.001	± 0.001					± 0.02	± 0.1

of these instruments, and the outer B component provides an excellent local reference.

For the time being we cannot directly determine the inclination of the inner orbit i_s, but it is strongly constrained by the requirement that M_A+M_C derived from the outer orbit must match the sum of the spectroscopic $M\times sin^3 i_s$ obtained from the inner orbit. This gives $sin^3 i_s$=0.705±0.016, and therefore i_s=117^o±1 or i_s=63^o±1. One of those two determinations is very close to the inclination of the outer orbit ($i_s - i_l \sim 5^o$). This probably points to a coplanar system, in keeping with a general tendency of close triple systems (Fekel 1981). One would however need to determine Ω_s and to resolve the i_s ambiguity to ascertain this.

As for Gl 570BC (Forveille et al. 1999), the combination of accurate radial velocity *and* angular separation data determines enough orbital parameters to derive the mass of each star with very good accuracy (Table 1), in spite of significant uncertainties on the elements constrained by the visual data alone: the system is fortunately close to edge-on, so that the relatively large uncertainty on i does not unduly propagate to $\sin^3 i$, and the derived masses are fairly accurate. We obtain relative precisions of 2.4% for both B and the AC barycenter. The short period spectroscopic orbit determines the mass ratio within AC very well, so that the individual masses of A and C also have this same precision. Amongst very low mass stars, only four systems have more accurate mass determinations (the three detached M-dwarf eclipsing binaries CM Dra, YY Gem and GJ 2069A; and Gl 570BC). The three components of Gl 866 are at least twice less massive than any of those. Gl 866A and B are slightly more massive than 0.1 $M_\odot$, and Gl 866C is slightly less massive.

4. Mass-luminosity relation

Henry et al. (1999) determine absolute magnitudes of $M_V = 15.58\pm0.07$ for Gl 866B and (implicitly) $M_V = 15.18\pm0.1$ for the AC pair, which is too close for *HST* to resolve. The relative areas of the cross-correlation "dips" in double/triple-lined multiple systems fortunately provides a welcome handle on the luminosity ratios in such unresolved systems. These areas are to first order proportional to the relative luminosities, with weaker dependences on effective temperature and metallicity (Mayor 1985), and [Fe/H] must here be identical for the three components, which formed from the same interstellar gas. For ELODIE spectra correlated with the M4 mask, we have unfortunately not yet calibrated the spectral type (and metallicity) dependence, and as a consequence we can only derive an approximate V-band luminosity ratio from the raw equivalent-width ratio. We obtain L_C/L_{AC}=0.158, which is consistent with the ∼2 magnitude difference in the V band between 0.12 $M_\odot$ and 0.095 $M_\odot$ 5 Gyr Baraffe et al. (1998) models. We conservatively assign a factor of 1.5 uncertainty to this ratio, which dominates the error bars on the luminosity of the C component. The A component on the other hand sufficiently dominates the light of the AC pair in the V band that even this quite large uncertainty does not

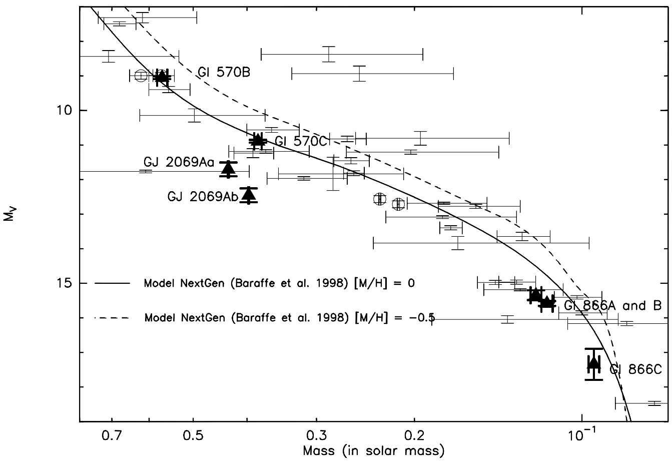

Fig. 4. V band mass-luminosity relation. The error bars without points are data from Henry and McCarthy (1993), Henry et al. (1999) and Torres et al. (1999). The circles represent the two well known M eclipsing binaries, YY Gem and CM Dra. The triangles represent our recent mesurements: GJ 2069A, Gl 570B and the three components of Gl 866. The two curves are 5 Gyr theoretical isochrones Baraffe et al. (1998) for two metallicities.

propagate into unduly large errors on its absolute V magnitude. We obtain $\mathrm{M_V}(A) = 15.34\pm0.14$ and $\mathrm{M_V}(C) = 17.34\pm0.45$.

Fig. 4 represents our present best attempt at a V-band mass-luminosity diagram. It shows the data points of Henry and McCarthy (1993), Henry et al. (1999) and Torres et al. (1999), as well as our recent measurements of Gl 866, GJ 2069Bab (Delfosse et al. 1999b), and Gl 570BC (Forveille et al. 1999). For this last source we obtain absolute magnitudes of ($\mathrm{M_V} = 9.05\pm0.05$ and $\mathrm{M_V} = 10.89\pm0.05$) from the V band photometry compiled by Leggett (1992), the HIPPARCOS parallax, and the V-band magnitude difference of Henry et al. (1999). The GJ 2069Bab eclipsing pair is clearly subluminous for its mass, most likely because its metallicity is significantly larger than solar (Delfosse et al. 1999b). The other objects are quite well fitted by the 5 Gyr isochrones of Baraffe et al. (1998), though the three Gl 866 component are slightly less luminous (∼0.5 mag) in the V band than the solar metallicity model for their mass. This discrepancy most likely reflects a known low level problem in the models: the present generation of M-dwarf atmospheric models is specifically suspected to lack an unidentified opacity source in the V passband, which at the effective temperature of late M dwarfs would contribute about ∼0.5 mag of extra absorption in this band (Allard, private communication). Alternatively, the observations of Gl 866 can be reconciled with the models if its metallicity is slightly larger than that of the sun. With the recent and forthcoming improvements in the accuracy of M-dwarf mass measurements, metallicity determinations will increasingly become a crucial limiting factor in accurate comparisons with stellar models, as has long been the case for more massive stars (e.g. Andersen 1991). Quantitative metallicity measurements of M dwarfs are difficult in the optical range (e.g. Valenti, Piskunov & Johns-Krull 1998), but K-band spectroscopy probably has the potential to reach the necessary accuracy (Allard, private communication).

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References

Andersen J. 1991, Astronomy and Astrophysics Review 3, 91.
Baraffe I., Chabrier G., Allard F. Hauschildt P. H, 1998, A&A 337, 403.
Baranne A., Queloz D., Mayor M., et al., 1996, A&AS 119, 389.
Blazit A., Bonneau D., Foy R., 1987, A&AS 71, 57
Delfosse X., Forveille T., Beuzit J.-L., et al., 1999a, A&A 344, 897.
Delfosse X., Forveille T., Mayor M., et al., 1999b, A&A 341, L63.
Doyon R., Nadeau D., Vallee P., et al., 1998, in SPIE Proceedings 3354, “Infrared Astronomical Instrumentation”, ed. A.M. Fowler, 760.
Fekel F. C., 1981, ApJ 246, 879.
Forveille T., Beuzit J.-L., Delfosse X., et al., 1999, A&A in press.
Harrington R. S., 1968, AJ 73, 190.
Heintz W. D., 1993, AJ 105, 1188.
Henry T. J., McCarthy D. W., 1993, ApJ 350, 334.
Henry T. J., Kirkpatrick J. D., Simons D. A., 1994, AJ 108, 1437.
Henry T. J., Franz O. G., Wasserman L. H., et al., 1999, ApJ 512, 864.
Leinert Ch., Jarheiss H., Haas M., 1986, A&A 164, L29
Leinert C., Haas M., Allard F., et al., 1990, A&A 236, 399.
Leggett S. K., 1992, ApJS 82, 365.
Mazeh T., Saham J., 1976, ApJ letter 205, L147.
Mayor M., 1985, in “Stellar radial Velocities”, IAU Coll.88, Eds. A.G.Davis Philip and D.W.Latham, Davis Press, Schenectady, USA, p.35
McCarthy D.W., Cobb M. L., Probst R. G., 1987, AJ 93, 1535
Rigaut F., Salmon D., Arsenault R., Thomas J., Lai O., Rouan D., Véran J.-P., Gigan P., Crampton D., Fletcher J.M., Stilburn J., Boyer C., Jagourel P., 1998, PASP 110, 152.
Torres G., Henry T. J., Franz O. G., Wasserman L. H., 1999, AJ 117, 562.
Valenti J. A., Piskunov N., Johns-Krull C. M., 1998, ApJ 498, 851.
Van Altena W.F., Lee J.T., Hoffleit D., 1995, The General Catalogue of Trigonometric Stellar Parallaxes, Fourth edition, Yale University Observatory (1995)