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Letter to the Editor

GJ 2069A, a new M dwarf eclipsing binary*

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Abstract. We have discovered a third detached M dwarf eclipsing binary system, for which we present an accurate radial velocity orbit and a preliminary light curve. From those data, we derive individual masses (0.433 and 0.397 $M_\odot$) with 0.4% accuracy, the most accurate to date for M dwarfs. Both stars are clearly sub-luminous for their mass, compared with solar metallicity stellar models or empirical mass-luminosity relations. Their spectral types are also later than expected. This indicates a metal-rich composition ($[M/H] \sim 0.5$). An infrared light curve and a more accurate trigonometric parallax would make this system a stringent test of our understanding of M dwarfs.

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

1. Introduction

The mass, metallicity and age dependencies of stellar luminosities and radii are still quite poorly calibrated for M dwarfs, which are the most numerous stars in our Galaxy. Below 0.6 $M_\odot$ the observational mass-luminosity relation (Henry and McCarthy 1993) is determined by only $\sim$15 stars, whose mass is typically measured (with the exception of two eclipsing systems) with 10-20% accuracy. M dwarf radius measurements are even fewer, and only available for the two eclipsing systems. This lack of observational calibration has significantly hindered (e.g. Chabrier and Baraffe 1995) the progress of theoretical models of these complex objects (dense plasma equation of state for the interior and cool dense atmospheres). Better constrained theoretical L(M,[Fe/H],T) relations could in turn be used to derive an improved very low mass stellar mass function from the better defined luminosity function.

As excellently reviewed by Andersen (1991; 1998), double line eclipsing binaries represent the only fundamental source of accurate stellar radii for dwarfs stars. They also provide mass measurements whose accuracy is unmatched, though adaptive optics and interferometric visual orbits are now catching up (e.g. Forveille et al., 1998). As a consequence, they play a fundamental role in validating and testing stellar models (Andersen, 1991; 1998). Selection effects unfortunately play against detecting eclipses in intrinsically faint and small stars, and only two well detached systems with significantly sub-solar masses had been known: YY Gem (M1V, 0.62 ± 0.03 and 0.57 ± 0.03 $M_\odot$; Leung and Schneider, 1978), and CM Dra (M4.5V, 0.2307 ± 0.0010 and 0.2136 ± 0.0010 $M_\odot$; Lacy, 1977, and Metcalfe et al., 1996).

We present here the discovery of a third M dwarf eclipsing binary, GJ 2069A, which provides a welcome addition at an intermediate mass. GJ 2069A is a nearby (d $=$ 12.8 pc, ESA 1997) M3.5V (Reid et al. 1995) system, which Delfosse et al. (1998) identified as a double line spectroscopic binary in the course of an M dwarf radial velocity survey at Observatoire de Haute Provence (CNRS, France). We have found eclipses during photometric follow-up with the 0.7m swiss telescope at the European Southern Observatory (La Silla, Chile). GJ 2069A has a fainter visual companion at $\sim$10", with common proper motion (Giclas, Slaughter and Burnham, 1959) and radial velocity (our measurements). GJ 2069B is itself double (Delfosse et al. 1998) and GJ 2069 is thus a quadruple system of M dwarfs.

2. Observations and data processing

2.1. Radial velocity

The 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 April 1998. 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 a one-bit (i.e. 0/1) template derived from an observed M4V spectrum (Delfosse et al., 1998). This process closely mimics the analog correlation used in the CORAVEL scanners (Baranne et al. 1979; Mayor 1985), and similarly produces a clean, quasi-gaussian, correlation pattern, where blending lines average out. Their residual effect is significant at high

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* Based on observations obtained at the Observatoire de Haute Provence (CNRS) and at the European Southern Observatory

Table 1. Individual radial velocity measurement

Julian date	V_r1	O-C	V_r2	O-C
50102.528	+72.363	+0.018	−70.039	−0.463
50180.417	+55.762	+0.208	−51.727	−0.435
50181.389	−62.507	−0.439	+76.540	−0.245
50181.442	−63.163	+0.207	+78.303	+0.101
50182.323	+26.906	+0.474	−20.842	−1.260
50182.369	+33.245	+0.267	−26.164	+0.545
50182.430	+41.317	+0.092	−37.358	−1.668
50182.476	+46.551	−0.449	−42.814	−0.836
50183.384	+31.521	+0.119	−23.989	+1.004
50183.427	+25.212	+0.008	−18.244	−0.001
50183.491	+16.000	+0.496	−8.064	−0.381
50228.354	−53.128	+0.387	+67.222	−0.111
50231.357	−62.646	+1.004	+79.392	+0.885
50389.667	−46.490	−0.096	+59.689	−0.028
50525.433	−50.097	−0.199	+63.745	+0.212
50921.344	−61.063	+0.005	+75.378	−0.317
50922.330	+29.951	−0.016	−23.427	+0.004
50923.332	+36.079	−0.091	−30.010	+0.176

S/N ratios (Delfosse et al., 1998), but varies on the scale of the line widths. For GJ2069A those are sufficiently smaller than the velocity amplitudes (10 km/s vs 140 km/s) that this can be considered as a random error rather than a systematic one. We have checked that the velocity residuals indeed show no systematic pattern when plotted as a function of phase. Table 1 lists the the individual measurements and their residuals (O-C) from the adjusted orbit. For most of those data the rms residuals are 0.4 km/s for the primary and 0.65 km/s for the secundary star. We used longer integration times after we realised GJ2069A could undergo eclipses, and those data (after JJ=50389 in Table 1) have better signal-to-noise ratios (S/N=15 instead of S/N=3-5) and their rms residuals is only 0.2 km/s. These values were used as standard errors in the weighting of the least square orbital adjustment, which was performed with ORBIT, a program derived from the code of Tokovinin (1992) and described in Forveille et al. (1998). The resulting adjusted parameters are listed in Table 2.

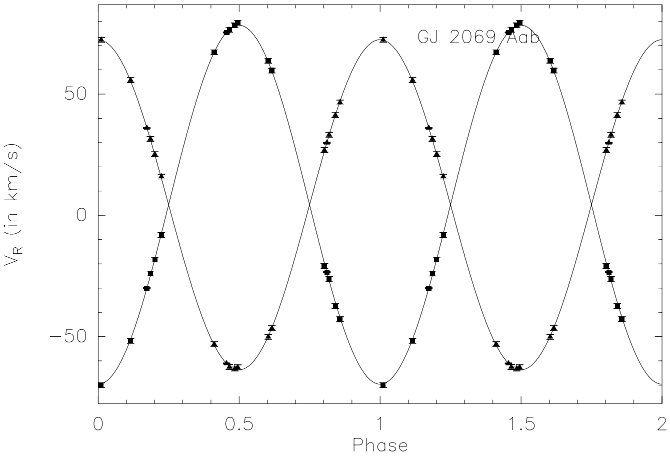

Fig. 1. Radial velocity orbit of GJ 2069A

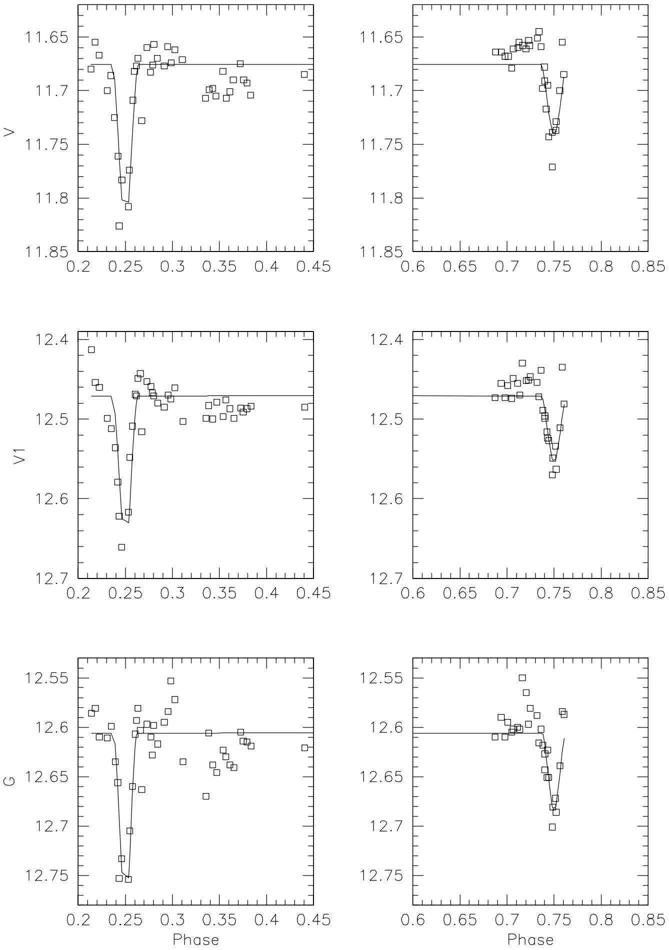

Fig. 2. Light curves of the primary (*right*) and secondary (*left*) eclipse for the V, V1 and G bands of the Geneva photometric system.

2.2. Photometry

Photometric observations were obtained during 8 nights between January and March 1998, using the double-beam 7 channel "P7" photometer (Burnet and Rufener 1979) on the 0.7m Swiss telescope at the European Southern Observatory (La Silla, Chile). Only the three reddest filters (V, V1, and G) provided usable data for this faint red star. GJ 2069A shows partial eclipses with amplitudes of, respectively, ∼0.2 mag and ∼0.15 mag for the primary and secondary eclipses (Fig. 2). The light curve has been analysed with EBOP (Etzel, 1980; Version 16), which is well suited to this wide detached eclipsing binary with negligible proximity effects. We fixed the period and eclipse epoch (Table 2) to their radial velocity values and only solved for the stellar radii, the inclination of the orbit, and the individual magnitudes of the 2 stars.

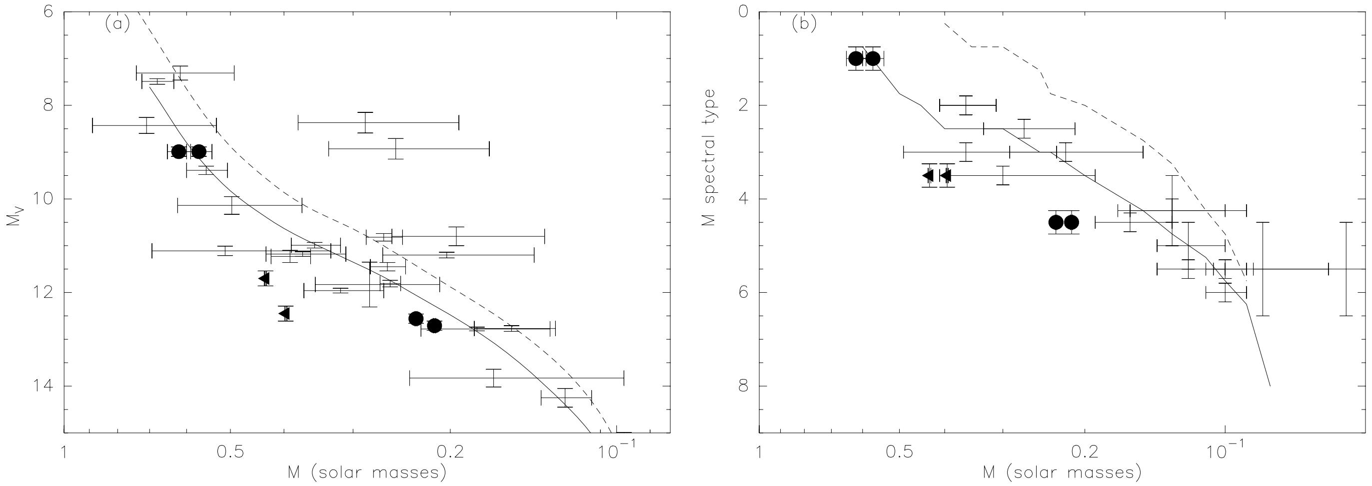

Fig. 3. **a** mass-luminosity and **b** mass-spectral type relations. Circles correspond to YY Gem and CM Dra, and triangles to the present measurements of GJ 2069A. The error-bars without points represent data from Henry and McCarthy (1993) for the mass-luminosity relation and from Kirkpatrick and McCarthy (1994) for the mass-spectral type relation. The solid and dashed lines represent [M/H]=0 and [M/H]=-0.5 theoretical 10 Gyr isochrones by Baraffe et al. (1998, and private communication).

3. Results

3.1. Stellar parameters

The radial velocity curve defines the period and the velocity amplitudes with high accuracy (Table 2). The minimum masses $M\ \sin^3 i$ are thus very well determined. The light curve by contrast is preliminary: it has relatively few data points, and more seriously, GJ 2069A is magnetically active, and as a consequence is an intrinsic photometric variable. The out-of-eclipse level of the light curve is thus imperfectly defined, limiting the accuracy of the orbital elements derived from the light curve. We have experimented with the level of this baseline, using either the mean baseline of the eight photometric nights or the baselines of the individual eclipse nights. We adopt the parameter range obtained for these different adjustments as conservative estimates of the probable errors, instead of the smaller EBOP internal errors. Infrared photometry would be much less affected by the intrinsic variability and would result in much improved stellar parameters.

In spite of the moderate light curve quality, the inclination angle, i is constrained to within 0.5°(Table 2), thanks to the well separated configuration ($(a_1 + a_2)/(R_1 + R_2) = 10$; in fact the mere existence of eclipses already implies $i >$84°and $\sin i > 0.995$). The standard error on $\sin^3 i$ is thus only 10^{-3}. Combined with the radial velocity orbit, it results in mass determinations which to our knowledge are the most accurate to date for M dwarfs, 0.4329 ± 0.0018 and 0.3975 ± 0.0015 M$_\odot$. The individual absolute V magnitudes of the two stars have errors of ~ 0.2 mag (at respectively M$_V$ 11.7 and 12.45), dominated by the uncertainties on the trigonometric parallax (78.05 ± 5.7 mas, ESA 1997). The stellar radii, on the other hand, are only determined with 10 and 15% standard errors and insufficiently precise for a significant comparison to theoretical models. We hope to obtain an infrared light curve to improve on this determination.

Table 2. Results of the fit to the radial velocity and light curves of GJ 2069A. The eccentricity is consistent with 0, as expected from tidal circularisation at this short period. It was held fixed for the final adjustment.

Orbital elements determined from the spectroscopic solution

Period (Days)	2.771468 $\pm$ 0.000004
T0 (Julian Day)	2450207.81397 $\pm$ 0.00079
K1 (km/s)	68.09 $\pm$ 0.11
K2 (km/s)	74.14 $\pm$ 0.13
V0 (km/s)	4.40 $\pm$ 0.06
a1 $\sin i$ (A.U.)	0.01735 $\pm$ 0.00003
a2 $\sin i$ (A.U.)	0.01889 $\pm$ 0.00003
M$_a$ $\sin^3$ i (M$_\odot$)	.4307 $\pm$ 0.0017
M$_b$ $\sin^3$ i (M$_\odot$)	.3956 $\pm$ 0.0014

Stellar parameters using both photometric and spectroscopic information

Inclination (Degrees)	86.7 $\pm$ 0.4
a1 (A.U.)	0.01737 $\pm$ 0.00003
a2 (A.U.)	0.01891 $\pm$ 0.00003
M$_a$ (M$_\odot$)	0.4329 $\pm$ 0.0018
M$_b$ (M$_\odot$)	0.3975 $\pm$ 0.0015
M$_{V_a}$ (magnitude)	11.7 $\pm$ 0.2
M$_{V_b}$ (magnitude)	12.45 $\pm$ 0.2
R$_a$ (solar radii)	0.49 $\pm$ 0.08
R$_b$ (solar radii)	0.33 $\pm$ 0.04

3.2. Discussion

Fig. 3 compares the mass, luminosity and spectral type of GJ 2069A with the Baraffe et al. (1998, and private communication) 10 Gyr isochrones. These models consistently combine stellar evolution models (e.g. Chabrier and Baraffe 1997) and non-grey atmospheric models (Allard et al. 1996). Their present generation still uses non-dusty atmospheres, but dust only becomes relevant at effective temperatures significantly lower than that of GJ 2069A (Allard, 1998). It is on the other hand unfortunate that the flux of GJ 2069A is only measured in the V band, which probably has a missing opacity source in present atmospheric models (Allard, private communication). The models therefore overestimate the V band flux by a few tenths of a magnitude. Fig. 3 also shows the data points of Henry and McCarthy (1993).

As compared with both solar metallicity models and observational relations, the components of GJ 2069A are clearly sub-luminous (by about 2 magnitudes) and their joint spectral type is too late (by about 2 sub-classes) for their mass (Fig. 3). This behaviour is qualitatively expected for stars whose metallicity is a few tenths larger than solar. There are at present no model for metal-rich M dwarfs, so that we cannot be very specific on the metallicity of GJ 2069A. As a rough indication, the distance in Fig. 3 between the two stars and the solar metallicity tracks is approximatively the same (in the other direction) as that between the theoretical tracks for [M/H]$= -0.5$ and [M/H]$= 0.0$ (Baraffe et al. 1998). If the track position scales linearly with metallicity, then GJ 2069A has approximately [M/H]$= +0.5$. Its space velocity (U$= 8\ \mathrm{km.s}^{-1}$, V$= -5\ \mathrm{km.s}^{-1}$, W$= -8\ \mathrm{km.s}^{-1}$, Delfosse et al. 1997) is typical of the young disk kinematic population, consistently with a large metallicity.

GJ 2069A provides a new accurate benchmark for M dwarf models, but its full potential will only be realized with a spectroscopic determination of the system's metallicity. The accuracy of M dwarf masses is generally improving, and metallicity will thus become increasingly significant in accounting for their luminosities. Quantitative metallicity measurements of M dwarfs are difficult however (e.g. Valenti, Piskunov & Johns-Krull, 1998) and significant progress will be needed to reach the necessary accuracy.

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