Accurate mass ratio and heating effects in the dual-line millisecond binary pulsar in NGC 6397

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ABSTRACT

By means of high-resolution spectra we have measured radial velocities of the companion (hereafter COM J1740−5340) to the eclipsing millisecond pulsar PSR J1740−5340 in the Galactic globular cluster NGC 6397. The radial-velocity curve fully confirms that COM J1740−5340 is orbiting the pulsar and enables us to derive the most accurate mass ratio ($M_{\text{PSR}}/M_{\text{COM}} = 5.85 \pm 0.13$) for any non-relativistic binary system containing a neutron star. Assuming a pulsar mass in the range $1.3 - 1.9 \, M_\odot$, the mass of COM J1740−5340 spans the interval $0.22 - 0.32 \, M_\odot$, the inclination of the system is constrained within $56^\circ \lesssim \iota \lesssim 47^\circ$ and the Roche lobe radius is $r_{RL} \sim 1.5 - 1.7 \, R_\odot$. A preliminary chemical abundance analysis confirms that COM J1740−5340 has a metallicity compatible with that measured for other stars in this metal-poor globular, but the unexpected detection of strong He I absorption lines implies the existence of regions at $T > 10,000 \, \text{K}$, significantly warmer than the rest of the star. The intensity of this line correlates with the orbital phase, suggesting the presence of a region on the companion surface, heated by the millisecond pulsar flux.

Subject headings: Globular clusters: individual (NGC 6397) — stars: evolution — binaries: close — pulsars: individual (PSR J1740−5340) — techniques: spectroscopic

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1. Introduction

During a systematic search of the galactic globular cluster (GC) system for millisecond pulsars (MSPs) carried out with the Parkes radio telescope, D'Amico et al. (2001a) discovered the binary millisecond pulsar PSR J1740–5340, in the nearby globular cluster NGC 6397. The pulsar displays eclipses at a frequency of 1.4 GHz for more than 40% of the $\sim 32.5$ hr orbital period and exhibits striking irregularities of the radio signal at all orbital phases. These features indicate that the MSP is orbiting within a large envelope of matter released from the companion (D'Amico et al. 2001b), whose interaction with the pulsar wind could be responsible for the modulated and probably extended X-ray emission detected with Chandra (Grindlay et al. 2001, 2002). By using the position of the MSP inferred from radio timing, Ferraro et al. (2001) identified a variable star (Star A, hereafter COM J1740–5340) whose optical modulation nicely agrees with the orbital period of the MSP. In particular, Ferraro et al. noticed that COM J1740–5340 is the first example of a MSP companion whose light curve is dominated by ellipsoidal variations, suggestive of a tidally distorted star, which almost completely fills (and is still overflowing) its Roche lobe.

Binary evolution calculations (e.g. Tauris & Savonije 1999; Podsiadlowski, Rappaport & Pfahl 2002) and the few optical detections (e.g. Hansen & Phinney 1998; Stappers et al. 2001) show that the common companion to a binary MSP is either a white dwarf or a very light ($\sim 0.01 - 0.03$ M$_{\odot}$) almost completely exhausted (and perhaps evaporating) star. If a MSP is located in a GC, dynamical encounters in the cluster core can also provide it with other kinds of companion and in fact a main sequence star has been probably identified as the star orbiting the MSP 47Tuc-W in 47 Tucanae (Edmonds et al. 2002). None of these hypotheses can be applied to COM J1740–5340: it is too luminous to be a white dwarf (V $\sim 16.5$, comparable to the turn-off stars of NGC 6397); its mass ($M_{\text{COM}} \geq 0.19$ M$_{\odot}$ for a 1.4 M$_{\odot}$ neutron star, D'Amico et al. 2001a) is not compatible with that of a very light stellar companion; its anomalous red color would require it to be perturbed if it was originally on the main sequence. As a consequence, a wealth of intriguing scenarios have flourished in order to explain the nature of the binary (see Possenti 2002, Orosz & van Kerkwijk 2003, Grindlay et al. 2002 for a review).

In any model, PSR J1740–5340 must have undergone at least one and perhaps multiple phases of “recycling” (Alpar et al. 1982). During this process significant accretion of mass ($\sim 0.1 - 0.7$ M$_{\odot}$) onto the neutron star (NS) is expected (van den Heuvel & Bitzaraki 1995; Burderi et al. 1999), but up to now no observation has measured a MSP NS mass unambiguously outside the narrow range of masses (average $1.35 \pm 0.04$ M$_{\odot}$) measured by

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Thorsett & Chakrabarty (1999) in a sample of binary pulsars statistically dominated by NS-NS relativistic systems. Besides clarifying the spin-up mechanism, finding a more massive NS could shed light also on the equation of state for nuclear matter (e.g. Cook, Shapiro & Teukolsky 1994).

Interestingly, PSR J1740–5340 and its companion constitute the optically brightest dual-line binary hosting a MSP, thus being a prime target for an accurate determination of both the binary parameters and the mass of a spun-up pulsar, while yielding the possibility of discriminating between the different suggested evolutionary paths. Hence, we have planned a coordinated spectro-photometric campaign using the ESO telescopes in La Silla and Paranal (both in Chile). While the photometric survey is still in progress, we present in this Letter the first spectroscopic results of the project, based on the analysis of a set of phase-resolved high-resolution spectra. Here we present the radial velocity curve of COM J1740–5340, the mass ratio of the system and preliminary estimates of its metallicity and effective temperature. The detailed analysis of the chemical abundance pattern of COM J1740–5340 will be presented in a forthcoming paper (Sabbi et al 2003, in preparation).

2. Observations and data analysis

The observations were performed in service mode with the Ultraviolet-Visual Echelle Spectrograph (UVES) mounted at the Kueyen 8m-telescope (UT2) of the ESO Very Large Telescope on Cerro Paranal (Chile). The spectra were obtained on 8 different nights from 2002 May to 2002 June (see Table 1) in order to cover the complete orbital period of the system. The dichroic beamsplitter #1 together with grisms #2 (centered at 3900 Å) and #3 (centered at 5800 Å) were used: this configuration allowed us to observe simultaneously two spectral ranges with the two arms (blue and red) of the spectrograph, covering the wavelength ranges 3280 – 4490 Å, 4725 – 5708 Å, and 5817 – 6725 Å. A 1′′ wide and 8′′ long slit was adopted, yielding a resolution of $R \sim 40,000$ at order centers. The exposure time for each spectrum (2600 sec, equal to $\sim 2\%$ of the system orbital period) enabled us to perform accurate phase resolved analysis, with a typical signal-to-noise ratio $S/N \geq 20$ per pixel, measured at the continuum level. All the spectra were extracted with the UVES pipeline (Ballester et al. 2000).
3. Results and Discussion

3.1. Radial Velocity Curve

The broad spectral range covered by the spectra allows the observation of a large number of spectral features. In particular we selected a set of $\sim 10^{-20}$ lines (comprising Fe, Ca, Na, Mg, Mn, Ti and Hγ) not contaminated by atmospheric and/or interstellar contributions. The Doppler-shifted wavelength of each line has been measured: the resolution of the UVES spectra allows very accurate measures of line centroids, with a typical formal accuracy of $\sim 0.02 - 0.05$ Å($\sim 1 - 3$ km s$^{-1}$). We have verified that the broadening of each line due to the variation of the velocity of the source along a 2600-sec integration is always negligible with respect to the intrinsic width of the lines. The line broadening due to rotation ($V_{\text{rot}} = 49.6\pm0.9$ km s$^{-1}$) permitted rejection of contaminating lines coming from nearby, non rotating objects (the system is in a crowded region, see Fig. 1 of Ferraro et al. 2001). The wavelength of each line has been converted to radial velocity (RV), taking into account for the heliocentric correction. In order to minimize spurious effects we measured RVs independently on the red and blue part of each spectrum and carefully checked that no significant offset was present. Then, all the RV measures obtained in each spectrum were averaged and a mean value was obtained.

In order to determine the amplitude $K$ of the RV curve and the systemic velocity $\gamma$, we fitted the data using the sum of a constant and a sinusoidal function, which is adequate to describe the orbital motion of this almost circular system (eccentricity $e < 10^{-4}$; D’Amico et al. 2001b). The best fit yields a radial-velocity amplitude $K = 155.8\pm3.6$ km s$^{-1}$ (1σ-error) with $\chi^2_0 = 0.99$. Inspection of Figure 1 shows that the absolute phase of the RV data matches that of the radio pulsar orbital motion very well (the radial velocities are null at inferior and superior conjunctions which, according to the convention of D’Amico et al. 2001b, correspond to orbital phases 0.25 and 0.75 respectively), confirming unambiguously that PSR J1740−5340 and COM J1740−5340 orbit each other. The systemic velocity is $\gamma = 17.7\pm2.3$ km s$^{-1}$, which is in perfect agreement with the radial motion of the cluster ($V_{6397} = 18.9\pm0.1$ km s$^{-1}$; Harris 1996), further confirming the membership $^8$. Table 1 lists the final heliocentric velocities after subtraction of the $\gamma$ velocity, where the standard deviation of the average has been assumed as an estimate of the error. The epoch and the

$^8$The small value of the difference $|\gamma - V_{6397}| < 3.6$ km s$^{-1}$ (1σ limit) suggests that the center of mass of the binary is now near apoastron of a highly elliptical orbit in the globular cluster. In fact, were the binary on an almost circular orbit at 11 core radii from the GC center, its relative line of sight velocity (estimated from the enclosed mass) would be of the order $\gtrsim 10$ km s$^{-1}$. This result supports the hypothesis that the binary has been recently kicked out of the core of NGC 6397 due the a dynamical interaction
orbital phase of the mid-time of each observation are also reported. The latter has been computed using the radio ephemeris of PSR J1740−5340 (D’Amico et al. 2001b). The resulting radial velocity-curve is shown in Figure 1.

3.2. Constraints on the mass of COM J1740−5340

Being a dual-line binary pulsar with a very bright companion, this system can be used to infer tight constraints to the masses of the components. The mass function \( f(M_{\text{COM}}) \) of COM J1740−5340 can be easily computed from the radial velocity amplitude \( K \) and the orbital period \( P_{\text{orb}} = 1.35405939 \pm (5 \times 10^{-8}) \) days (D’Amico et al. 2001b):

\[
f(M_{\text{COM}}) = \frac{M_{\text{PSR}}^{3} \sin^{3} i}{(M_{\text{COM}} + M_{\text{PSR}})^{2}} = \frac{K^{3} P_{\text{orb}}}{2\pi G} = 0.530 \pm 0.038 \, M_{\odot},
\]

where \( M_{\text{PSR}} \) and \( M_{\text{COM}} \) are the masses of the pulsar and the companion star, \( i \) is the inclination of the orbital plane with respect to the line-of-sight and the errors are quoted at the 1\( \sigma \)-level, as everywhere in the following. The mass ratio \( q = M_{\text{PSR}}/M_{\text{COM}} \) can be derived by combining eq. (1) with the mass function of the MSP obtained by D’Amico et al. (2001b):

\[
f(M_{\text{PSR}}) = \frac{M_{\text{COM}}^{3} \sin^{3} i}{(M_{\text{COM}} + M_{\text{PSR}})^{2}} = (2.6442 \pm 0.0003) \times 10^{-3} \, M_{\odot}.
\]

We obtain \( q = 5.85 \pm 0.13 \), which is the most accurate estimate (~2% error) ever obtained for the mass ratio in any non-relativistic binary comprising a neutron star and in particular a recycled pulsar. In order to completely solve for the binary parameters one needs the orbital inclination of the system. However, for a reasonable choice of the neutron star mass (in the range 1.0 – 2.5 \( M_{\odot} \), Shapiro & Teukolsky 1983), the precise measurement of the mass ratio reduces the allowed space of the parameters to a very narrow strip in the \( M_{\text{PSR}} \) vs. \( i \) diagram (see Fig. 2).

A further constraint on the inclination can be inferred from the ellipsoidal modulation of the light curves of COM J1740−5340 (the ongoing photometric analysis will be presented elsewhere). Preliminary results, based on an incomplete coverage of the orbit (Orosz & van Kerkwijk 2003) indicate \( i > 46^\circ \) (at 2\( \sigma \)) which implies (Fig. 2) \( M_{\text{PSR}} \lesssim 2.0 \). This lower limit on \( i \) well agrees with that \( (i > 46^\circ.3) \) derived from our determination of the rotational velocity \( V_{\text{rot}} \) of COM J1740−5340 assuming a photometric radius of the companion in the range \( (1.60 \pm 0.17 \, R_{\odot}) \) measured by Orosz & van Kerkwijk (2003).

Hence in Table 2, we have listed some of the orbital parameters of the system derived assuming the three reference cases of \( M_{\text{PSR}} = 1.3, 1.5, 1.9 \, M_{\odot} \). In all these cases, the radius
of the Roche lobe of COM J1740−5340 matches with the dimension estimated from HST photometry (Ferraro et al. 2001). The implied range of the companion masses (0.22 M⊙ ≤ M_{COM} ≤ 0.32 M⊙) fits all the evolutionary models proposed so far (Burderi, D’Antona & Burgay 2002; Orosz & van Kerwijk 2003; Grindlay et. al 2002; Ergma & Sarna 2003), whose discrimination will be greatly assisted by the detailed measurement of the chemical abundances (Sabbi et al 2003, in preparation).

3.3. Chemical composition analysis: a surprising result

In order to perform a preliminary chemical abundance analysis, the two spectra taken under the best seeing conditions (at phases 0.021 and 0.564, close to the quadratures, see Table 1) have been corrected for the RV and then combined, thus attaining S/N ∼ 45 in the wavelength region around 5900 Å, near the Na\textsc{i} D lines. The estimate of the metallicity has been obtained inspecting the equivalent width of about 40 useful lines (mostly Fe\textsc{i}) and by assuming a gravity (log g = 3.2) compatible with the position of COM J1740−5340 in the color-magnitude diagram. Figure 3 shows a zoom-in on that spectral region of the normalized spectrum taken at phase 0.02.

In summary, the main features of the spectra are: (1) strong broadening of the lines due to the rotation of the star; (2) a low value of the metallicity [Fe/H] ∼ −2 and an excess of α-elements such as Na\textsc{i}, Mg\textsc{i}, and Si\textsc{i}; (3) the presence of many lines of low excitation, together with a few weak lines of ionized elements. Feature (2) is fully compatible with the results derived for other stars in this cluster (Gratton et al. 2001), and further confirms the membership of the object to NGC 6397. Feature (3) indicates that the effective temperature is low, in agreement with the red color of the source. The H\textsc{α} line wings imply \( T_{\text{eff}} \approx 5530\pm70 \) K, confirming the previous estimate of Ferraro et al. (2001).

The most fascinating result of the preliminary abundance analysis is the presence of He\textsc{i} absorption lines at 5875.6 Å and at 6678.2 Å. The former line is clearly visible in Figure 3. Such a spectral feature is completely unexpected in a low-temperature star like COM J1740−5340, being the signature of photospheric regions at \( T > 10,000 \) K. Remarkably, the He\textsc{i} lines are clearly visible in all the spectra, with the exception of the two taken at phases 0.199 and 0.363, when COM J1740−5340 is located between the MSP and the observer. This result suggests the existence of a region of the star (facing the pulsar) at a temperature significantly larger than the rest of the surface. More careful analyses are under way to assess the dimensions of the heated region. However, the relatively small orbital variation of the colors (hence effective temperature) of the star (Orosz & van Kerwijk 2003, Kaluzny, Rucinski, & Thompson. 2002) is suggestive of a heated area, smaller than the
cross section of the surface of COM J1740−5340 visible from the MSP. At the same time, the rotation profile of the \( \text{He}^i \) lines would suggest that this warmed region extends rather longitudinally along the companion surface (an equatorial strip?). As an example, a region facing the pulsar with a dimension \( \sim 3 - 5\% \) of the Roche lobe radius of COM J1740−5340 and with \( T \sim 10^4 \) K, could produce a brightening of 0.02–0.04 mag in the light curves of COM J1740−5340 near orbital phase 0.75 (when we see the hemisphere of the companion facing the pulsar). This could explain the asymmetry in the light curves seen around the minimum at phase 0.75 (Ferraro et al. 2001).

The existence of a strongly heated portion of the surface of a MSP companion is not uncommon (e.g. Stappers et al. 2001) and naturally calls for the effects of the energetic flux of particles and electromagnetic waves released from the MSP. What is peculiar in COM J1740−5340 is the strip-like shape and the equatorial location of the heated region. This would suggest that the pulsar energetic flux is preferentially emitted in the orbital plane of the binary with a highly flattened shape. Noticeably, a similar planar emission pattern of the pulsar wind has been invoked in order to explain the origin of the X-ray inner ring surrounding the Crab, whose spin axis is believed to be nearly orthogonal to the plane containing the ring (Hester et al. 2002).

In summary, if confirmed by future analysis, the existence of a warmed strip onto the surface of COM J1740−5340 would be of great significance: first, a strongly anisotropic emission could enhance the amount of the pulsar rotational energy impinging onto the companion. This could trigger yet largely unmodeled effects during the radiation-driven evolution of a MSP binary system (D’Antona 1996). Secondly, location and extension of the heated strip could be used for inferring the MSP spin and magnetic axes orientations, helping in discriminating among the different evolutionary scenarios proposed so far.

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REFERENCES


Fig. 1.— The large dots are the radial velocity determinations for COM J1740−5340. The solid line represents the best-fit sinusoidal curve. The small open squares are the radial velocity determinations for PSR J1740−5340 derived from timing measurements and the radio ephemeris (D’Amico et al. 2001b). The dashed line represents the fitted velocity curve of the pulsar.
Fig. 2.— Mass of PSR J1740−5340 and orbital inclination of the binary. The allowed range of values are constrained to lie within the narrow strip whose borders (dotted lines) are the 1σ boundaries derived from the mass ratio of the system. Lines of constant mass for COM J1740−5340 are also shown (dashed lines) and labeled with the assumed mass value. The vertical dot-dashed line represents the 2σ lower limit on the orbital inclination derived from the modeling of the light curves of COM J1740−5340 (Orosz & van Kerkwijk 2003). This lower limit is nearly coincident with that inferred from the rotational velocity of the companion.
Fig. 3.— Portion of the normalized spectrum taken at $\phi = 0.02$ in the Na\textsc{i} D lines region (the telluric Na\textsc{i} lines have been removed for clarity). The spectrum has been smoothed with a boxcar of 3 pixels, and not shifted to rest wavelengths; the observed RV is $-145.4$ km s$^{-1}$. The He\textsc{i} absorption line at 5875.6 Å is clearly visible; Na\textsc{i} D lines and the strong He line are indicated.
Table 1. Radial velocity measurements

<table>
<thead>
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<th>MJD</th>
<th>Orbital Phase</th>
<th>Radial Velocity (km s(^{-1}))</th>
</tr>
</thead>
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<tr>
<td>52413.22761</td>
<td>0.0204</td>
<td>(-150.6 \pm 8.0)</td>
</tr>
<tr>
<td>52405.26219</td>
<td>0.1374</td>
<td>(-96.7 \pm 8.0)</td>
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<td>52416.17728</td>
<td>0.1988</td>
<td>(-36.7 \pm 10.1)</td>
</tr>
<tr>
<td>52404.21301</td>
<td>0.3630</td>
<td>101.3 (\pm 4.6)</td>
</tr>
<tr>
<td>52434.27455</td>
<td>0.5640</td>
<td>138.0 (\pm 8.9)</td>
</tr>
<tr>
<td>52422.19896</td>
<td>0.6460</td>
<td>97.9 (\pm 4.5)</td>
</tr>
<tr>
<td>52414.26020</td>
<td>0.7830</td>
<td>(-40.0 \pm 5.7)</td>
</tr>
<tr>
<td>52440.14142</td>
<td>0.8968</td>
<td>(-130.4 \pm 8.9)</td>
</tr>
</tbody>
</table>

Table 2. Derived parameters of the PSR J1740–5340 system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ratio, (q)</td>
<td>(5.85 \pm 0.13)</td>
</tr>
<tr>
<td>Temperature of COM J1740–5340, (T_{\text{eff}}) (K)</td>
<td>(5530 \pm 70)</td>
</tr>
<tr>
<td>Radial-velocity amplitude of COM J1740–5340, (K) (km s(^{-1}))</td>
<td>(155.8 \pm 3.6)</td>
</tr>
<tr>
<td>Mass of PSR J1740–5340, (M_\odot)</td>
<td>1.30 1.50 1.90</td>
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<tr>
<td>Mass of COM J1740–5340, (M_\odot)</td>
<td>0.22 0.26 0.32</td>
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<tr>
<td>Inclination angle, (i) (deg)</td>
<td>56 51 47</td>
</tr>
<tr>
<td>Orbital separation, (a) ((R_\odot))</td>
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<tr>
<td>Roche lobe radius of COM J1740–5340, (r_{RL}) ((R_\odot))</td>
<td>1.5 1.6 1.7</td>
</tr>
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