PHOTOMETRY AND SPECTROSCOPY OF THE OPTICAL COMPANION TO THE PULSAR PSR J1740–5340 IN THE GLOBULAR CLUSTER NGC 6397

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ABSTRACT

We present photometric and spectroscopic observations of the optical companion to the millisecond radio pulsar PSR J1740–5340 in the globular cluster NGC 6397. An analysis of the photometric variability in the B, V, and I bands indicates an inclination of the system of 43°9′ ± 2°1′ if the optical companion fills its Roche lobe (a semidetached configuration). The spectroscopic data show a radial velocity variation with a semi-amplitude of $K = 137.2 ± 2.4$ km s$^{-1}$, and a system velocity $\gamma = 17.6 ± 1.5$ km s$^{-1}$, consistent with cluster membership. We use these results to derive a mass of the optical companion of $M_1 = 0.296 ± 0.034 M_\odot$ and $M_2 = 1.53 ± 0.19 M_\odot$ for the pulsar. There is evidence for secular change of the amplitude of the optical light curve of the variable measured over 7 years. The change does not have interpretation and its presence complicates reliable determination of the absolute parameters of the binary.

Key words: binaries: close — globular clusters: individual (NGC 6397) — pulsars: individual (PSR J1740–5340)

1. INTRODUCTION

The millisecond radio pulsar (MSP) PSR J1740–5340 was discovered in the field of the globular cluster NGC 6397 by D’Amico et al. (2001a) in the course of a survey conducted with the Parkes radio telescope. Follow up pulsetiming observations (D’Amico et al. 2001b) led to a determination of several parameters of the system, including orbital period, projected semimajor axis and mass function. Ferraro et al. (2001) identified the optical companion of the pulsar with a variable object detected earlier by Taylor et al. (2001). Photometry presented by both groups shows that the optical companion to the MSP is a relatively bright star ($V = 16.7$). It is located about 0.2 mag to the red of the turnoff region and about 0.7 mag below the base of the cluster red giant branch on the $V$/$V-I$ color-magnitude diagram. Such an unusual position can be explained by assuming that the optical companion to the pulsar is an evolved star containing a helium core surrounded by a hydrogen-rich envelope (e.g., Ergma & Sarna 2002). Supposedly, it has lost a significant fraction of its original mass due to the Roche lobe overflow triggered by an attempted ascent on the red giant branch. Remarkably, despite being located only 26″ from the cluster center, the variable is a relatively isolated star (see Fig. 2 in Ferraro et al. 2001), permitting optical observations with ground-based telescopes. In this paper we present the results of photometric and spectroscopic observations obtained to determine the masses for both components of the binary.

The evolutionary status of PSR J1740–5340 has been discussed by Burderi, D’Antona, & Burgay (2002) and Ergma & Sarna (2002). Both groups present some detailed scenarios, which attempt to explain the current status of the binary and the observed position of its optical component on the cluster color-magnitude diagram. The system has been detected in the X-ray domain with the Chandra observatory by Grindlay et al. (2001, 2002).

2. OBSERVATIONS

2.1. Photometric Observations

Observations in B, V, and I filters were obtained with the 2K$^2$ Tek No. 5 CCD camera on the 2.5 m du Pont telescope at Las Campanas Observatory (LCO) in 2002 May and June. The cluster was observed on seven nights for a total of 32 hr. The camera has a pixel scale of 0′′259 pixel$^{-1}$. Only 600 rows of the CCD were read out during observations of the cluster in order to reduce dead time between exposures, resulting in a field of view of 8.65 × 2.60 arcmin$^2$ centered on the cluster. The dead time between images taken in the same filter amounted to 20 s.

Preliminary processing of the CCD frames was done with the IRAF-CCDPROC package. For the photometric analysis we used stacked images, each consisting of three to eight individual short exposures. All co-added images span less than 10 minutes and in most cases less than 6 minutes. In the order of $B$, $V$, and $I$ bands, the total number of stacked images is 69, 197, and 59, while average effective exposure times are 136, 75, and 50 s. In the same order of the bands, the average seeing for the stacked images is 1′′04, 1′′03, and 0′′87.

We used the ISIS-2.1 image subtraction package (Alard & Lupton 1998; Alard 2000) to extract differential light curves of the optical counterpart of the pulsar, following the prescription given in the ISIS.V2.1 manual. For each band a template image was constructed from several stacked images.

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4 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
frames of the best image quality. Magnitude zero points for the ISIS differential light curves were measured from the template images, using the DAOPHOT/ALLSTAR software package (Stetson 1987), and aperture corrections were measured with the DAOGROW program (Stetson 1990). Instrumental magnitudes were transformed to the standard BVI system using the following relations:

\[ V = v - 0.0134(B - V) + 0.1279(X - 1.25) + 0.7737, \]
\[ B = b - 0.0690(B - V) + 0.2243(X - 1.25) + 1.1254, \]
\[ I = i + 0.0059(V - I) + 0.0382(X - 1.25) + 1.3080, \]

where \( b, v, \) and \( i \) are instrumental magnitudes and \( X \) is the air mass. The coefficients of the transformation were measured from 12 observations five Landolt fields (Landolt 1992) obtained on the night May 2 (UT). The standard fields were observed over a range of air mass covering 1.16 to 2.00. Figure 1 shows the residuals of the photometric solution. We conclude that the uncertainties of the zero points of our photometry do not exceed 0.02 mag.

BVI light and color curves of the variable are presented in Figures 2 and 3. We phased our observations using the ephemeris derived from radio timing observations from D'Amico et al. (2001b). The phase was shifted by 0.25 so that at phase 0.0 the optical component is in conjunction (in front of the radio pulsar). Throughout this paper we use the ephemeris

\[ \text{HJD} \left( \text{min I} \right) = 2,451,750.549336(7) + E \times 1.35405939(5), \]

where the numbers in parentheses represent formal 3 \( \sigma \)

\[ 5 \text{ The ephemeris derived by D’Amico et al. (2001b) locates phase 0.0 at the ascending node of the pulsar orbit. This convention implies that for an inclination } i = 90^\circ \text{ at phase 0.75, the observer sees the side of the companion facing the pulsar. In our convention the observer sees that side of the companion at phase 0.50.} \]
uncertainties, in units of the last significant digit, of the very high precision determination of D’Amico et al. A program based on the KWEE algorithm (Kwee & van Woerden 1956) was used to determine moments of both minima for the phased light curves. It was found that after averaging the results for all 3 filters the observed photometric minima occurred 0.006 \pm 0.004 of the orbital period earlier than times of minima predicted by the above radio ephemeris.

The phase coverage is generally good, with the exception of the quadrature at phase 0.75, which is covered by only a few data points in the \textit{V} filter and only single data points in the \textit{B} and \textit{I} filters. The light curves show symmetric minima, and there is no indication of any significant difference in the light level at the two quadratures. The color curves show some reddening near phase 0.5. All of these features indicate that the observed variability is caused mostly, if not entirely, by ellipsoidal effects. In particular, the slight difference in the depths of the minima (with the secondary minimum being deeper) is consistent with such an interpretation.

In Table 1 we list \textit{BVI} magnitudes observed at the extrema of the light curves as determined by parabolic fits to points located with phase \pm 0.05 from a given extrema. Note lack of the phase coverage in \textit{B} and \textit{I} bands around the phase 0.75. The full amplitude of the light variation is 0.172(4), 0.152(4), and 0.139(5) mag for the \textit{B}, \textit{V}, and \textit{I} bands, respectively. We note that the \textit{HST} observations collected in 1999 April indicate a noticeably larger amplitude.

Figure 5 shows a mean spectrum of the optical companion to PSR J1740–5340 from our observations on 2002 June 8 UT and July 29 UT, all shifted to the systemic 2.2. Spectroscopic Observations

Spectra were obtained with the B&G spectrophotograph on the 6.5 m Baade telescope at LCO on the nights of (UT dates)
The relative velocity (HD 74000 observations, and HD 116064 for the July observations. HD 74000 was used as the template for all of the May and June observations of the XCSAO program. The results are given in Table 2. HD 1998 (Beveridge & Sneden 1994) compared with the cluster metallicity of [Fe/H] = −2.07 (Beveridge & Sneden 1994) running under IRAF, and errors were adopted from the ephemeris given by equation (4). The results were $K_1 = 136.03 \pm 2.75$ km s$^{-1}$, and $\gamma = 17.62 \pm 1.69$ km s$^{-1}$. The heliocentric velocity of NGC 6397 is 19.2 km s$^{-1}$ (Gebhardt et al. 1995), and we conclude that this is a cluster member. It has to be noted, however, that, because of the nonspherical shape of the optical companion, its radial velocity curve is expected to show some departures from purely sinusoidal motion. Therefore, the above values of $K_1$ and $\gamma$ have to be treated as first approximations only for further improvement in a combined photometric-spectroscopic solution given in the next section. The radial velocity observations are presented in Figure 6 using the GaussFit solution, and the velocity curve of the pulsar itself ($K_2 = 26.6121 \pm 0.0004$ km s$^{-1}$, as derived from the radio pulsar timing data, D’Amico et al. 2001b) shifted to a systemic velocity of 17.6 km s$^{-1}$.

3. PHOTOMETRIC AND SPECTROSCOPIC SOLUTIONS

To solve the light and velocity curves of the optical component of the binary pulsar, we used the Wilson & Devinney (1971, hereafter W-D) model as implemented in the 1986 version of the code. The code is described in some detail by Wilson (1979) and by Leung & Wilson (1977). The MINGA$^6$ minimization package (Plewa 1988) was used for the actual fitting of the observed light curves and the derivation of the system parameters. It was assumed that the only source of light in wavelengths covered by our data is the surface of the nondegenerate component. Using the $T_{\text{eff}}$ versus $B - V$ calibration of Alonso et al. (1996), we estimated an effective temperature $T_{\text{eff}} = 5630$ K.$^7$ Appropriate values of the limb-darkening coefficients were taken from Wade & Rucinski (1985): $X_B = 0.679$, $X_V = 0.577$, $X_I = 0.40$. The

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**TABLE 2**

Radial Velocities of the Optical Companion of PSR J1740–5340

| HJD − 2,450,000 | Phase | $V$ (km s$^{-1}$) | $\sigma V$ |
|-----------------|-------|----------------|----------|
| 2424.579        | 0.785 | −105.35        | 17.04    |
| 2424.598        | 0.798 | −110.31        | 17.77    |
| 2424.625        | 0.818 | −110.80        | 9.11     |
| 2424.652        | 0.838 | −84.19         | 8.17     |
| 2424.676        | 0.856 | −76.78         | 6.78     |
| 2424.704        | 0.876 | −81.83         | 7.41     |
| 2424.729        | 0.895 | −67.08         | 6.67     |
| 2424.763        | 0.920 | −60.64         | 7.23     |
| 2424.787        | 0.938 | −53.80         | 9.18     |
| 2424.815        | 0.959 | −36.47         | 12.08    |
| 2424.839        | 0.977 | −21.75         | 15.59    |
| 2424.877        | 0.004 | 7.81           | 16.79    |
| 2425.591        | 0.531 | −3.34          | 11.43    |
| 2425.615        | 0.550 | −30.00         | 18.01    |
| 2425.878        | 0.744 | −115.51        | 11.12    |
| 2426.567        | 0.244 | 151.80         | 11.17    |
| 2426.591        | 0.270 | 160.33         | 9.35     |
| 2426.615        | 0.288 | 157.36         | 10.92    |
| 2426.713        | 0.358 | 121.86         | 12.63    |
| 2426.736        | 0.388 | 117.63         | 14.28    |
| 2428.785        | 0.885 | −78.08         | 7.40     |
| 2433.609        | 0.454 | 62.58          | 9.38     |
| 2433.858        | 0.637 | −83.88         | 11.63    |
| 2484.499        | 0.032 | 50.19          | 4.63     |
| 2484.523        | 0.050 | 70.68          | 4.35     |
| 2484.553        | 0.072 | 73.76          | 5.62     |
| 2484.576        | 0.108 | 79.94          | 5.63     |
| 2484.600        | 0.107 | 90.81          | 7.44     |
| 2484.623        | 0.124 | 107.70         | 8.52     |
| 2484.654        | 0.147 | 130.84         | 8.62     |
| 2484.678        | 0.164 | 130.32         | 9.18     |

$^6$ The MINGA package can be obtained from ftp://ftp.camk.edu.pl/camk/tomek/Minga/newest.

$^7$ As noted by the referee, the effective temperature could be derived from the spectrum of the variable. We refrained from doing this because of the low spectral resolution of our data and the necessity of a rather complex calibration against standards of low and well-matching metallicity.
gravity-brightening coefficient was set to $g_1 = 0.32$, an appropriate value for stars with convective envelopes. The secondary component was assumed to be dark and very small so that it does not influence the shape of the light curve. This was achieved by setting $T_2 = 1000 \, \text{K}$ and adopting a very high value of the gravitational potential $\Omega_2 = 900$.

There are some arguments for assuming that the binary is in a semidetached configuration, filling its Roche lobe. This case is advocated by Burderi et al. (2002), who point out that a relatively high rate of mass loss of $M < 10^{-10} \, \text{M}_\odot \, \text{yr}^{-1}$ is implied by estimates of the mass of the gaseous envelope causing the radio eclipses of PSR J1740–5340 to last about 40% of the orbital period. Further evidence supporting a semidetached configuration is the fact that the binary harbors an extended X-ray source, suggestive that the X-ray flux results from the interaction of a relativistic wind with mass loss from the optical companion (Grindlay et al. 2001). We show below that there is no evidence for heating from the optical companion by the MSP, and so the mass loss is likely to arise from Roche lobe overflow. In this case the mass needed to power the extended X-ray source could be supplied directly through the inner Lagrangian point.

However, we cannot completely reject the possibility that the binary has a detached configuration, and in the following two subsections we present light and radial velocity solutions for both semidetached and detached configurations.

### 3.1. Semidetached Configuration

The shape of optical light curves of the binary indicates that the observed variability is dominated by ellipsoidal effect. Experiments show that the light curves can be in fact quite well approximated by a sine function. That means that any model used to reproduce the observed light curves could have no more than one free parameter, the sine-curve amplitude. In our light-curve solution conducted for the assumed semidetached configuration, that free parameter translates into $i$, the inclination of the binary orbit.

We started the analysis by modeling the light curves with an assumed value of the mass ratio $q = m_2/m_1 = 5.11$, where the index 1 refers to the optical component and where $q$ is derived from the $K$ amplitudes listed in the previous section. The W-D code was run in Mode-4, the configuration with the primary component filling its Roche lobe.

The solution converged to a model with inclination $i = 44^\circ.12 \pm 2^\circ.15$. The next step involved a determination of the radial velocity amplitude $K_1$ by fitting the observed velocity curve with model curves generated with the W-D code. The W-D code allows one to calculate the non-dimensional velocity curve, $v_{1\text{obs}}$, and the $K_1$ amplitude is calculated using the relation:

$$v_{1\text{obs}} = v_{1\text{th}} \times K_1 \times \sin(i) \times (1 + 1/q) + \gamma,$$

where $v_{1\text{obs}}$ is the observed photocenter velocity and $\gamma$ is the systemic velocity. We derive $K_1 = 137.2 \pm 2.4 \, \text{km s}^{-1}$ and $\gamma = 17.6 \pm 1.5 \, \text{km s}^{-1}$. This in turn gives a new value of the mass ratio $q = K_2/K_1 = 5.15$, which was used to get an improved solution of the light curves. This procedure converged after one more iteration, and we derive the following set of final parameters: $i = 43^\circ.9 \pm 2^\circ.1$, $K_1 = 137.2 \pm 2.4 \, \text{km s}^{-1}$, and $\gamma = 17.6 \pm 1.5 \, \text{km s}^{-1}$.

In Figure 7 we show the residuals for the final solution of the light curves. Note that, while the fit is generally good, some systematic errors are present in fits obtained for the $V$ and $B$ bands at the level of 0.01 mag. These systematic errors cannot be corrected without introducing any additional features to the pure W-D model. The deviations have a tendency to diminish with increasing wavelength and indicate the presence of some extra light near phase 0.5, where we see the hemisphere of the optical component facing the pulsar. Some irradiation processes may be responsible for this effect. Figure 8 shows residuals for the model fit to the radial velocity curve. The observed residuals are consistent with the formal errors of the measured velocities. Figure 9 shows how the $\chi^2$ statistic changes as a function of assumed inclination of the binary. The fit is excellent with a well-defined minimum in $\chi^2$ at $i \sim 44^\circ$.

Using these values of the radial velocity amplitudes and the inclination we obtain masses of the components of the binary pulsar PSR J1740–5340 of $M_1 = 0.296 \pm 0.034 \, \text{M}_\odot$ and $M_2 = 1.53 \pm 0.19 \, \text{M}_\odot$. Note that the errors of the masses are dominated by the accuracy of the derived inclination. The absolute size of the orbit is $A = 6.30 \pm 0.09 \, \text{R}_\odot$, and the average radius of the optical component is $R_1 = 1.67 \pm 0.02 \, \text{R}_\odot$.

### 3.2. Detached Configuration

In the detached configuration the light curve of the system depends mostly on the inclination $i$ and the gravitational potential $\Omega_1$. These two parameters are strongly
correlated, and therefore we decided to obtain a grid of solutions for several fixed values of $i$. The results are given in Table 3, which lists the adopted value of inclination, the average relative radius of the optical component, its ratio to the inner Roche lobe radius, and the $\chi^2$ of the model. Note that, for a given mass ratio $q$, the radius $r_1$ is only a function of the gravitational potential $\Omega_i$. Table 3 shows that fits of comparable quality were obtained for the whole range of adopted inclinations. In particular, the solution for $i = 45^\circ$ is very close to the semidetached configuration considered in the previous section. Taken at face value, the fits for the detached case and $i > 50$ are marginally better than the fit derived for the semidetached case. Hence, we believe that we cannot with confidence determine the configuration of the binary solely from the light-curve solution. Table 4 lists some absolute parameters of the binary corresponding to the solutions from Table 3. Note that the formal errors of the masses in Table 4 do not include an uncertainty in the inclination, as it was fixed for each entry in the table.

An additional and entirely independent constraint on the system inclination arises from information about its cluster membership. Reid (1998) and Reid & Gizis (1998) have used main-sequence fitting to derive $V$-band apparent distance moduli for NGC 6397 of $12.80 \pm 0.1$ and $12.69 \pm 0.15$, respectively. Adopting a distance modulus ($m - M)_V = 12.72 \pm 0.18$ and using $h_M = 16.71$ (see Table 1) we obtain $h_M = 3.99 \pm 0.18$ as an estimate of the average absolute magnitude of the optical component for an assumed reddening of $E(B - V) = 0.18$ (Reid & Gizis 1998). This gives $h_M = 3.72 \pm 0.18$ for $BC = 0.27$, which is appropriate for the observed color and metallicity of the star (Houdashelt, Bell, & Sweigert 2000). Using the relation $R_1/R_0 = (L/L_0)^{1/2} \times (T_{\text{eff}}/T_{\text{eff}}_0)^2$, we obtain $R_1 = 1.68 \pm 0.14 R_0$. This apparently eliminates all solutions with $i > 47^\circ$ listed in Table 4.

A further constraint on the inclination could come from a measurement of the rotational velocity of the optical companion. Our spectra do not have high enough resolution; however, the optical companion is bright enough that such measurements could be made with echelle spectrographs on 6.5 m class telescopes.

### Table 3

**Light-Curve Solutions for Detached Configuration and Fixed Inclination**

| $i$ (deg) | $\Omega_i$ | $\langle r_1 \rangle$ | $\langle r_1 \rangle/\langle r_{\text{lim}} \rangle$ | $\chi^2$ |
|-----------|------------|----------------------|----------------------|--------|
| 90        | 10.113(18) | 0.201(7)             | 0.75                 | 285    |
| 85        | 10.102(18) | 0.210(7)             | 0.79                 | 281    |
| 80        | 10.067(18) | 0.212(8)             | 0.80                 | 271    |
| 75        | 10.013(18) | 0.215(8)             | 0.81                 | 262    |
| 70        | 9.941(19)  | 0.219(8)             | 0.82                 | 258    |
| 65        | 9.850(19)  | 0.224(8)             | 0.84                 | 258    |
| 60        | 9.743(18)  | 0.230(9)             | 0.86                 | 266    |
| 55        | 9.620(18)  | 0.239(10)            | 0.90                 | 286    |
| 50        | 9.489(17)  | 0.249(10)            | 0.94                 | 317    |
| 47        | 9.412(10)  | 0.257(5)             | 0.96                 | 336    |
| 46        | 9.388(13)  | 0.259(7)             | 0.97                 | 342    |
| 45        | 9.365(11)  | 0.263(7)             | 0.99                 | 345    |

### Table 4

**Absolute Parameters Corresponding to Solutions from Table 3**

| $i$ (deg) | $K_1$ | $A/R_0$ | $R_1/R_0$ | $M_1/M_0$ | $M_2/M_0$ |
|-----------|-------|---------|-----------|-----------|-----------|
| 90        | 136.2 | 4.38(6) | 0.88(3)   | 0.099(3)  | 0.51(2)   |
| 85        | 136.2 | 4.40(6) | 0.92(3)   | 0.100(3)  | 0.51(2)   |
| 80        | 136.2 | 4.45(7) | 0.94(4)   | 0.104(3)  | 0.53(2)   |
| 75        | 136.2 | 4.53(7) | 0.98(4)   | 0.110(3)  | 0.56(3)   |
| 70        | 136.3 | 4.66(7) | 1.02(4)   | 0.120(4)  | 0.61(3)   |
| 65        | 136.3 | 4.83(7) | 1.08(4)   | 0.133(4)  | 0.68(3)   |
| 60        | 136.4 | 5.06(7) | 1.16(5)   | 0.153(4)  | 0.78(4)   |
| 55        | 136.5 | 5.35(8) | 1.28(5)   | 0.181(5)  | 0.93(4)   |
| 50        | 136.7 | 5.72(8) | 1.42(6)   | 0.222(7)  | 1.14(4)   |
| 47        | 136.8 | 5.99(9) | 1.54(2)   | 0.255(7)  | 1.31(6)   |
| 46        | 136.9 | 6.09(9) | 1.58(4)   | 0.268(8)  | 1.38(6)   |
| 45        | 137.0 | 6.20(9) | 1.63(4)   | 0.282(8)  | 1.46(7)   |
4. DISCUSSION

An additional complication in the interpretation of the optical observations of the optical companion is the fact that its light curve clearly evolves on a timescale of a few years. The range of variability in the \( V \) band has changed from \( \Delta V = 0.23 \) mag in 1995 to \( \Delta V \approx 0.15 \) in 2002. We discuss briefly three possible interpretations of these changes, as follows:

1. **Secular change of the inclination of the orbit of binary.** Assuming a semidetached configuration the observed change of \( \Delta V \) requires a change of orbital inclination of about 8° (from \( i = 52^\circ \) in 1995 to \( i = 44^\circ \) in 2002). There are a few eclipsing binaries with observed variation in the inclination of their orbital plane due to an interaction with a third body (Drechsel et al. 1994; Milone et al. 2000). However, the rate of variation is at a level of a few tenths of a degree per year at best. Pulsar timing observations covering a 6 month interval (D’Amico et al. 2001b) show no evidence for a dynamical interaction of PSR J1740–5340 with a hypothetical third body. Further radio timing observations of the pulsar should provide very strong limits on any changes of orientation of the orbital plane of the binary.

2. **Variable “third light” contributions to the light curve.** Luminous streams of gas around pulsar or variable heating of the optical component of the system could lead to changes in the light curve. However, in this case we should observe not only changes in the amplitude of the light curves but also changes in the maximum observed light. One may estimate how much of third light is needed to diminish \( \Delta V \) from \( \approx 0.23 \) (1995 season) to \( \approx 0.15 \) (2002 season), where \( \Delta V \) is the magnitude difference for phases 0.25 and 0.5. Denoting the flux level at phase 0.25 in 1995 season by \( \bar{F}_{\text{1995}} \), we obtain \( \bar{F}_{\text{1995}} = 0.48 \bar{F}_{\text{2002}} \). That in turn implies that at quadrature the system would be brighter by 0.42 mag in 2002 season as compared with 1995 season. Our data show no indications for any change of light level at quadratures between the 1995 and 2002 seasons that would exceed 0.02–0.03 mag.

3. **Intrinsic variability of the optical companion.** It is possible that the observed variability is intrinsic to the optical companion, perhaps in the form of starspot activity. The companion has a high rotational velocity if it is tidally locked (\( v_{\text{rot}} \approx 50 \text{ km s}^{-1} \)), and such a high rotational velocity in a fully convective atmosphere normally leads to the formation of starspots. We have used W-D code to perform some light-curve simulations for a model including one dark spot. The starting point was the light-curve solution obtained for the semidetached configuration and the 2002 data. It turns out that one may indeed increase the depth of the minimum observed at phase 0.5 to 0.23 mag, as seen in 1995 season, by putting a dark spot in a region around inner Lagrangian point L1. Specific parameters of such a spot are \( \Delta T = 1000 \) K and radius equal to 20° (as seen from the center of the star). The corresponding change in \( V \) magnitude at quadratures would then amount to only 0.02 mag. It is worth noting in this context that light curves presented by Ferraro et al. (2001; Fig. 4) show a clear asymmetry at minimum light, which occurs at phase 0.5. The spot hypothesis offers a possible way to explain such a distortion. The observed red colors of the variable indicate that it possesses a convective envelope. This fact, connected with the rapid rotation enforced by tidal interaction, points toward a high level of magnetic activity likely to be displayed by the star. High-resolution spectroscopy covering the region of the H and K lines of Ca II could offer an easy way of checking on the level of such activity.

We do not have a definite explanation for the observed variations in the amplitude of the light curves. The hypothesis invoking stellar spots seems to be a viable option for a moment. Clearly further monitoring of the system would be desirable.

5. SUMMARY

Our analysis indicates that the observed modulation of the optical light from the optical companion of the pulsar PSR J1740–5340 can be fully explained by ellipsoidal variations. There is no indication of any detectable light due to heating of the companion by radiation from the pulsar. However, the light-curve amplitude appears to evolve on a timescale of a few years, a phenomenon without a clear interpretation, which may systematically affect our results.

An analysis of the radial velocity curve indicates that, if the velocities are modeled with a simple sinusoidal variation, neglecting the nonspherical shape of the optical component, \( K_1 = 137.2 \pm 2.4 \text{ km s}^{-1} \) and \( \gamma = 17.6 \pm 1.5 \text{ km s}^{-1} \). The measured systemic velocity of the system is consistent with cluster membership of the binary. Gebhardt et al. (1995) obtained for NGC 6397 \( \gamma = 19.2 \pm 0.5 \) and measured \( \Delta V_{\text{rad}} \approx 5.0 \text{ km s}^{-1} \) at radius \( r \approx 30'' \) from the cluster center. This observation is interesting in light of speculations about the possible formation of the system in a relatively recent three-body interaction (e.g., Grindlay et al. 2002).

The low amplitude of the observed light variations and the lack of optical eclipses precludes a determination of the inclination of the orbit of the binary without making any assumptions. A well-constrained solution for the light and velocity data (taking into account the photocenter velocity correction) was obtained by assuming a semidetached configuration for the binary, resulting in \( i = 43.9 \pm 2.1 \) for the system inclination and \( M_1 = 0.296 \pm 0.034 \ M_\odot \) and \( M_2 = 1.53 \pm 0.19 \ M_\odot \) for the masses of optical companion and the pulsar, respectively. Measurements of the masses of radio pulsars are known to show a remarkably narrow Gaussian mass distribution, with \( M = 1.35 \pm 0.04 \ M_\odot \) (Thorsett & Chakrabarty 1999), and our measurement of the mass of PSR J1740–5340 is consistent with this result.

Relaxation of the assumption of a semidetached configuration leads to light-curve fits of similar quality for a wide range of inclinations, \( 44^\circ < i < 90^\circ \). If we assume a bolometric correction of the optical companion of \( BC = -0.27 \), then the distance modulus of the cluster constrains the inclination to a range of \( 44^\circ < i < 47^\circ \). In such a case our spectroscopic data give \( M_2 \gtrsim 1.31 \pm 0.06 \ M_\odot \) as a lower limit on the pulsar mass. The lower limit to the mass of the optical companion is \( M_2 \gtrsim 0.255 \pm 0.007 \ M_\odot \). The low mass of the optical companion of PSR J1740–5340 resulting from our analysis supports evolutionary scenarios presented recently by Burderi et al. (2002) and Ergma & Sarna (2002).

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