The puzzling properties of the Helium White Dwarf orbiting the millisecond pulsar PSR J1911−5958A in NGC 6752[1]

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ABSTRACT

We have used phase-resolved high-resolution images and low resolution spectra taken at the ESO Very Large Telescope, to study the properties of the low-mass Helium White Dwarf companion to the millisecond pulsar PSR J1911−5958A (hereafter COM J1911−5958A), in the halo of the Galactic Globular Cluster NGC 6752. The radial velocity curve confirms that COM J1911−5958A is orbiting the pulsar and allows to derive a systemic velocity of the binary system nicely in agreement with that of NGC 6752. This strongly indicates that the system is a member of the cluster, despite its very offset position ($\sim$ 74 core radii) with respect to the core. Constraints on the orbital inclination ($\gtrsim 70°$) and pulsar mass ($1.2-1.5$ $M_{\odot}$) are derived from the mass ratio $M_{PSR}/M_{COM} = 7.49 \pm 0.64$ and photometric properties of COM J1911−5958A. The light curve in B-band shows two phases of unequal brightening (Δmag$\sim$ 0.3 and 0.2, respectively) located close to quadratures and superimposed on an almost steady baseline emission: this feature is quite surprising and needs to be further investigated.

Subject headings: Globular clusters: individual (NGC 6752) — stars: evolution — binaries: close — pulsars: individual (PSR J1911−5958A) — techniques: spectroscopic — techniques: photometric

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1. Introduction

PSR J1911−5958A is a binary millisecond pulsar (MSP) discovered on 1999 in the nearby Globular Cluster (GC) NGC6752, during a search performed with the Parkes radio telescope at 1.4 GHz (D'Amico et al. 2001). Accurate celestial coordinates and orbital parameters for this binary system have been first derived from ~ 18 months of pulsar timing observations (D'Amico et al. 2002) and recently refined (Corongiu et al. 2006) using a much longer data span. The pulsar has a spin period of 3.26 ms and follows an almost circular orbit ($e \sim 3 \times 10^{-6}$, Corongiu et al. 2006) with an orbital period of 0.84 day.

An unprecedented characteristic of this binary is his position: it is located at $\sim 6.4'$ from the cluster center (D'Amico et al. 2002), corresponding to about 74 core radii (Ferraro et al. 2003b). This is the most off–centered pulsar among the entire catalog of MSPs whose position in the parent cluster is known. Since dynamical friction should have driven the binary towards the GC center in a timescale much shorter than the age of the cluster (Colpi, Possenti & Gualandris 2002), the location of PSR J1911−5958A has been interpreted as a evidence for a strong dynamical interaction which occurred $\lesssim 1$ Gyr ago in the cluster core (D'Amico et al. 2001, Ferraro et al. 2003b), leading to the ejection of the binary towards the outskirts of NGC 6752. Dynamical events are not unexpected in the dense stellar enviromnent of a GC, but clear observational signatures of them are still very rare (e.g. the cases of PSR JB21227+11C in M15, Phinney & Sigurdsson 1991, or PSR J0514−4002A in NGC 1851, Freire et al. 2004). Moreover, in the case of PSR J1911−5958A it has been conjectured that a binary black hole of intermediate mass (Colpi, Possenti & Gualandris 2002; Colpi, Mapelli & Possenti 2003) may have been involved in the interaction.

Stimulated by the implications of the peculiar position of PSR J1911−5958A in NGC 6752, we have undertaken a program of optical observations, in the aim of shedding light on the origin and evolution of the binary and for assessing its belonging to the cluster. As a first step, we have identified the radio pulsar's optical companion (hereafter COM J1911−5958A) by using high-resolution images taken at ESO Very Large Telescope (Ferraro et al. 2003a; analogous identification was independently achieved by Bassa et al. 2003). The object turned out to be a relative faint ($B \simeq 22.1$ mag), blue star ($(B-V) = 0.1$ mag), whose position in the color-magnitude diagram lies between the Main Sequence and the Carbon Oxygen White Dwarf cooling sequence. The detailed comparison with theoretical evolutionary tracks (Serenelli et al. 2002) suggested that it is a Helium White Dwarf (He-WD) of mass in the range $0.17 - 0.20\ M_{\odot}$, with a temperature $T_{\rm eff} \approx 11,000\ K$, a gravity $\log g \approx 6.2$, a luminosity $L = 0.03 - 0.04\ L_{\odot}$, a radius $R = 3 - 4 \times 10^{9}$ cm and a cooling age in the range $1.2 - 2.8$ Gyr (Ferraro et al. 2003a).

In this letter we present the results of a second group of photometric and spectroscopic observations performed at ESO Very Large Telescope (VLT) in order to determine the radial velocity (§2) and light curve (§4) of COM J1911−5958A. The mass ratio of the system is derived in §3, as well as contraints on the pulsar mass and the orbital inclination of the binary.

2. Radial velocity curve of COM J1911−5958A

The analyzed spectra has been retrieved from the ESO Science Archive Facility. Observations were performed by using the *FOcal Reducer and low resolution Spectrographer 1* (FORS1) mounted at the *Antu* 8m-telescope (UT1) of the ESO-VLT on Cerro Paranal (Chile). The spectra series were obtained during 6 different nights from 2004 July to 2004 August, using the Long Slit Spectroscopy (LSS) operation mode and the B-Bessel Grism, which cover the spectral range $3400 - 5900$Å. The $1''$ wide and $6'.8$ long slit was adopted, yelding a dispersion of 1.2 Å/pixel. The exposure time for each spectrum (2500 sec, $\sim 4\%$ of the system orbital period), and the total number of different spectra analyzed (23), ensured a typical signal-to-noise ratio $S/N \simeq 10$ per pixel (measured at the continuum level), allowing to collect a good phase-resolved set of data. The data reduction has been perfomed by using the standard IRAF[1] tools. Raw images has been first corrected for bias and flat-field and decontaminated from cosmic rays, then the spectra were extracted and wavelenght calibrated. Using the task IDENTIFY and polynomial fit with a 4-th order function, the accuracy of the wavelenght calibration results ≤ 0.01 Å. Each spectrum has been corrected for the Earth motion and reported to a common heliocentric system using the task RVCORRECT.

The spectral range covered by the spectra allows the observation of several spectral features, in particular the Hydrogen Balmer-lines from H_β to $H(7)$. The Doppler-shifted wavelenght of each line has been measured by using the SPLOT task, fitting with a gaussian function all the features. The wavelenght of each line has been converted to a radial velocity (RV), then all the RVs measured for each spectra has been averaged and a mean value was obtained (accounting for the heliocentric correction). Only the 21 RV determinations resulting from the average of at least five measures have been used. The mid-point of each observations has been converted to a orbital phase by adopting the orbital period and the epoch of the ascending node for the pulsar orbit as given by the radio ephemeris (Corongiu et al. 2006). Phases 0.0 and 0.5 correspond to the quadratures, phase 0.25 to the inferior conjunction of the companion (i.e. when COM J1911−5958A is at its closest position with

[1]IRAF is distribuited by the National Optical Observatory which is operated by the Association of Universities for Research in Astronomy Inc., under cooperative agreement with the National science Foundation

respect to the observer) and phase 0.75 to the superior conjunction. In order to determine the amplitude K of the radial velocity curve and the systemic velocity γ of the binary system, we have fitted the data by using a function which is the sum of a constant and a sinusoid, adequate to describe the almost perfectly circular orbit of COM J1911−5958A. The best fit curve yields $K = 237.5 \pm 20.0$ km s^{-1} and $\gamma = -28.1 \pm 4.9$ (1σ uncertainties are used here and everywhere in the paper) and is reported in Figure 1.

3. The mass ratio

The systemic velocity of the binary system is in agreement with the published radial motion of the globular cluster ($v_{\rm NGC6752} = -27.9 \pm 0.8$, Harris et al. 1996, catalog revision 2003). This lends further support to the cluster membership of the binary. Given the central 1-D dispersion velocity of NGC 6752 (9-15 km s^{-1}, Drukier et al. 2003), the expected 1-D dispersion velocity for objects of mass $1.4 - 1.7$ M$_\odot$ (corresponding to the most likely total mass of the binary, see later) and located at the projected position of PSR J1911−5958A with respect to the cluster center is 2-3 km s^{-1} (Mapelli, private communication). This is fully compatible with the value of the difference $\Delta v_{\rm 1D} = |\gamma - v_{\rm NGC6752}| \lesssim 6$ km s^{-1}. Moreover, the small value of $\Delta v_{\rm 1D}$ may indicate that the binary is now near apoastron of a highly elliptical orbit in the potential well of the globular cluster. In fact, were the binary on an almost circular orbit at 74 core radii from the GC center, its line of sight velocity with respect to the cluster center (Sabbi et al. 2004), as estimated from the enclosed mass, would be of the order $\gtrsim 12$ km s^{-1}. All these considerations support the hypothesis that the binary has been recently kicked out of the core of NGC 6752 due to a dynamical interaction (see §1).

We are in the position of inferring the ratio between the masses of the two stars in the binary. The mass function of the pulsar, as measured from radio observation, is (Corongiu et al. 2006):

$$f(M_{PSR}) = \frac{M_{\rm COM}^3 \sin^3 i}{(M_{\rm COM} + M_{\rm PSR})^2} = 0.002687849(6)\ {\rm M}_\odot, \qquad (1)$$

whereas the mass function of the companion, derived from the present spectroscopic observations results:

$$f(M_{\rm COM}) = \frac{M_{\rm PSR}^3 \sin^3 i}{(M_{\rm COM} + M_{\rm PSR})^2} = \frac{K^3 P_{\rm orb}}{2\pi G} = 1.13 \pm 0.29\ {\rm M}_\odot, \qquad (2)$$

where $P_{\rm orb} = 0.83711347700(1)$ days (Corongiu et al. 2006), K is the amplitude of the radial velocity curve, $M_{\rm PSR}$ and $M_{\rm COM}$ are the masses of the pulsar and the companion, i is the inclination of the normal to the orbital plane with respect to the line-of-sight, and the brakets report the 1σ errors on the last significant digit. The mass ratio $q = M_{\rm PSR}/M_{\rm COM}$ can be derived by combining eq. (1) with eq. (2), and results $q = 7.49 \pm 0.64$.

Solving separately for the masses of the two stars would require a determination of the orbital inclination: the relation between $M_{\rm PSR}$ and i for different values of $M_{\rm COM}$ is displayed in Figure 2, for a reasonable choice of the neutron star mass ($1 - 2.5$ $M_\odot$, Shapiro & Teukolsky 1983). The measured mass ratio (with its uncertainty) selects a narrow strip of allowed parameters in Figure 2. In particular, $M_{\rm PSR} > 1.1$ $M_\odot$ and $M_{\rm COM} > 0.16$ $M_\odot$ (1σ limits). Moreover, $M_{\rm COM} \lesssim 0.30$ $M_\odot$ and the orbital inclination is $\gtrsim 60°$. Tighter constraints can be obtained in the hypothesis that the companion is a He-WD: in this case, the range of masses determined by Ferraro et al. (2003a) implies that the system is almost edge-on ($i \gtrsim 70°$) and the pulsar mass is in the range $1.2 - 1.5$ $M_\odot$. It is worthwhile to note that the latter mass interval brackets the values of all neutron star masses accurately measured so far (Lorimer 2005), but one case (Nice et al. 2005).

4. The puzzling light curve of COM J1911−5958A

The photometric observations were performed in service mode at the *Antu* 8m-telescope of the ESO-VLT during two nights in 2003, March and May (ESO Program ID 071.D-0232), and six nights in 2004, August (ESO Program ID 073.D-0067A). All the images were acquired using B-band filter in high-resolution mode with the FORS1 camera. In this configuration the instrumental pixels scale is $0.1''$ pixels^{-1} and the Field of View of the 2048×2048 pixels Tektronix-CCD is $3'.4 \times 3'.4$. The data comprise twenty-one 600s and five 360s exposures, centered roughly less then $1'$ far from the PSR J1911−5958A nominal position (D'Amico et al. 2002). The observations on 2004 were planned in order to evenly distribute along the orbit of the binary system.

From all the original frames we have extracted a subimage of 500×500 pixels, roughly centered on the nominal position of PSR J1911−5958A. The scientific images have been reduced using ROMAFOT, a package specifically developed to achieve accurate photometry in crowded fields (Buonanno et al. 1983); it enables the visual inspection of the quality of point-spread function (PSF) procedure. PSF best-fitting has been performed for all the images separately, and the mask with the star position obtained from the best-quality image was adapted to each image. The instrumental magnitudes have been reported to a common photometric system, then we have obtained a catalog with the coordinates and the instrumental magnitudes for all the stars common to all the images. We have performed the photometric calibration using two different and indipendent methods. First, magnitudes have been matched to four standard stars (Landolt 1992) observed under photometric conditions in the B-band. Then, all the ~ 100 stars in our catalog in common with the B-band catalog published by Ferraro et al. (2003) have been used to derive the photometric zero-point. The two resulting calibrations are fully consistent within a few hundredths of magnitude.

A periodicity search was carried out on the photometric data set using GRATIS (GRaphycal Analyzer of TIme Series), a software package developed at the Bologna Astronomical Observatory (see previous applications in Ferraro et al. 2001). Since the period ($P = 0.839 \pm 0.002$ day) obtained from the COM J1911−5958A variability curve turned out to be fully consistent with that obtained from the radio time series of PSR J1911−5958A, a phased light curve has been produced (Figure 3) assuming the same orbital parameters used in §2. The different symbols in Figure 3 mark series of B-magnitudes obtained in different observing nights (hence different companion's orbits): in particular, empty and starred symbols are used for the pointings of 2004, whereas filled symbols (clustering at about phase 0.6) refer to observations of 2003.

The result is really surprising: COM J1911−5958A shows two phases of strong enhancement of the luminosity located close to the quadratures and extending for about 20% of the orbit each. The primary maximum occurs between phases 0.5 and 0.6 (a more precise positioning is prevented by the lacking of useful data in that range) with a flux variation of $\gtrsim 0.3$ mag in less than 1 hr: orbital location and rapidity of the brightening are confirmed in two different orbits. A secondary maximum, corresponding to a brightening of ~ 0.2 mag appears at about phase 0.05, presenting a less steep raise with respect to the primary peak (in this case only the decay from the maximum is observed in two different orbits). Outside the peaks, the source displays an almost steady luminosity at an average $B = 22.11 \pm 0.02$. In particular the B-band luminosity at orbital phase ~ 0.6 does not show any significant fluctuation between the 2003 and the 2004 data (the pointings of 2003 unfortunately did not cover other orbital phases).

These features are unusual and intriguing. The modulation of the optical light curve of the companion to a MSP is most often driven by the heating of one emisphere of the star (whose rotation is syncronized with the orbital period) due to the radiation coming from the pulsar: see for example the cases of PSR B1957+20 (Callanan, van Paradijs, & Rengelink 1995) and PSR J2051-0827 (Stappers et al. 2001) in the Galactic field and 47 Tuc U and 47 Tuc W in the GC 47 Tucanae (Edmonds et al. 2001, 2002). For PSR J1911−5958A the square of the ratio ($\xi_1 \sim 100$) between the orbital separation ($\sim 4.5 - 5 R_\odot$) and the radius of the companion (inferred from the off-peaks luminosity and the effective temperature, Ferraro et al. 2003a) is much larger than the ratio ($\xi_2 \sim 25$) between the rotational power of the pulsar[2] and the bolometric off-peaks luminosity of COM J1911−5958A. This implies that the modulation due to the heating effect ($\Delta(\text{mag}) = 2.5 \log[1 + (\eta/2)(\xi_2/\xi_1^2)]$, where $\eta < 1$ is the efficiency of the process) should be negligible ($\Delta(\text{mag}) \lesssim 0.001$) and in fact no flux enhancement is detected around phase 0.75, when the side of the companion facing the pulsar is visible.

Ellipsoidal variations due to the tidal deformation of the companion are known to produce a light curve with two peaks at quadratures (see for example the case of PSR J1740−5340 in NGC 6397, Ferraro et al. 2001), but the light curve is expected to have maxima of equal amplitude and clear minima (of unequal depth) at conjunctions. Moreover, tidal deformations are expected to be insignificant for a companion whose radius is ~ 20 times smaller than the radius of its Roche lobe.

Accretion of matter onto a compact object can generate a variety of modulated optical emission (e.g. Frank, King & Raine 2002), but neither the neutron star nor the He-WD in this system can be suitable sources of plasma feeding accretion-related processes at the present epoch. The timing stability and the extension of the time span of the radio observations of PSR J1911−5958A (Corongiu et al. 2006) tend also to exclude the existence of a residual accretion disk around the pulsar or the presence of a third optically faint body which is now pouring mass in the binary.

One may wonder if the optical modulation can be intrinsic to the He-WD. Non-radial pulsations of WDs can produce optical fluctuations at a level of ~ 0.2 mag, but for a star with $T_{\text{eff}} \approx 11,000\ K$ the expected modulation occurs at periods significantly shorter than 0.84 days (e.g. Bergeron et al. 2004). However, a few high magnetic field ($\sim 10^8$ G) isolated WDs (see e.g. PG 1031+234, Piirola & Reiz 1992, and EUVE J0317−855, Barstow et al. 1995) display variations of $\lesssim 0.3$ mag at the supposed rotational period of the star. In the framework of an oblique rotator model for the WD, these photometric modulations have been interpreted with changes with the rotational phase of the mean magnetic field strenght over the visible stellar surface (which in turn affects the opacity along the line of sight: Ferrario et al. 1997). A suitable geometry (leading to an alternate exposure of both the magnetic polar caps of the WD) may in principle produce a double peaked light curve, but we note that all the aforementioned effects have been observed only in relatively massive

[2]It is calculated with the usual formula $\dot{L}_{\text{rot}} = (4\pi^2)I\dot{P}/P^3$ where I (assumed equal to 10^{45} g cm^2) is the neutron star moment of inertia, P the spin period and $\dot{P}$ the spin period derivative. Given the observed proper motion and the off-centered position of PSR J1911−5958A in NGC 6752, the value of $\dot{L}_{\text{rot}}$ can be underestimated at most a factor 3 as a consequence of the centrifugal acceleration of the pulsar and of the combined effects of the gravitational potentials of the Galaxy and of the globular cluster (Corongiu et al. 2006). This possible correction leaves the discussion about the heating effect unchanged.

WDs ($\sim 0.5 - 1.0$ $M_\odot$) insofar.

Given this puzzling scenario, further data are clearly necessary for constraining the origin of the optical modulation in this system, namely phase resolved multi color (UBVRI) photometry, complemented with higher resolution spectroscopy. In this respect, polarimetric observations would be particularly enlightening, since the detection of linear/circular polarization variation at the rotational/orbital period would be a strong signature of a highly magnized WD.

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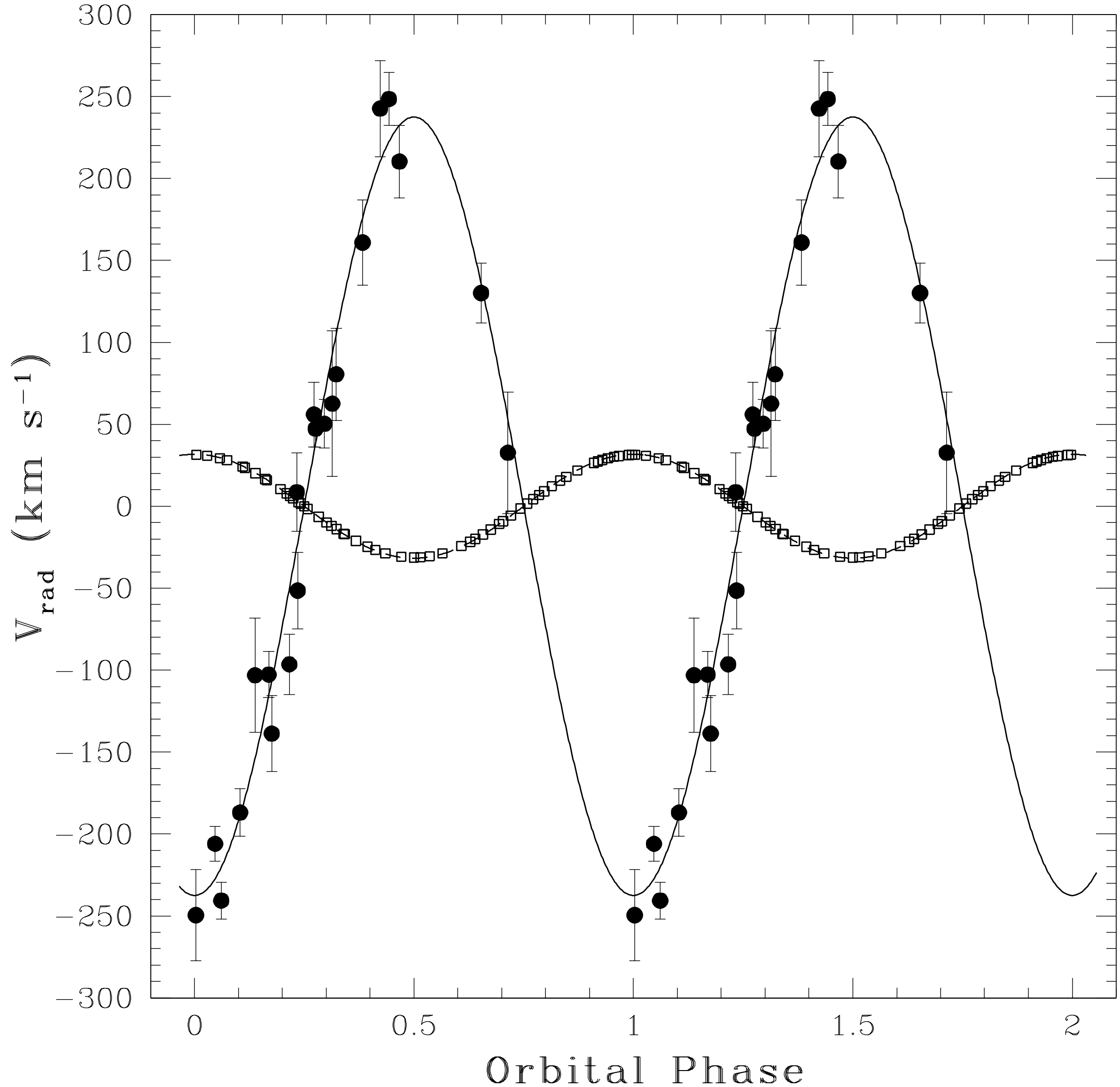

Fig. 1.— Velocity curves of COM J1911−5958A (*large dots*) and PSR J1911−5958A (*empty squares*). The data for the pulsar are derived from timing measurements and the radio ephemeris (Corongiu et al. 2006). Error bars for the pulsar radial velocity are smaller than the size of the symbols. The *dashed* and the *solid lines* represent the best-fit to the velocity data with a sinusoidal curve, for the pulsar and the companion star, respectively. The systemic velocity $\gamma = -28.1$ km s^{-1} of the binary has been subtracted.

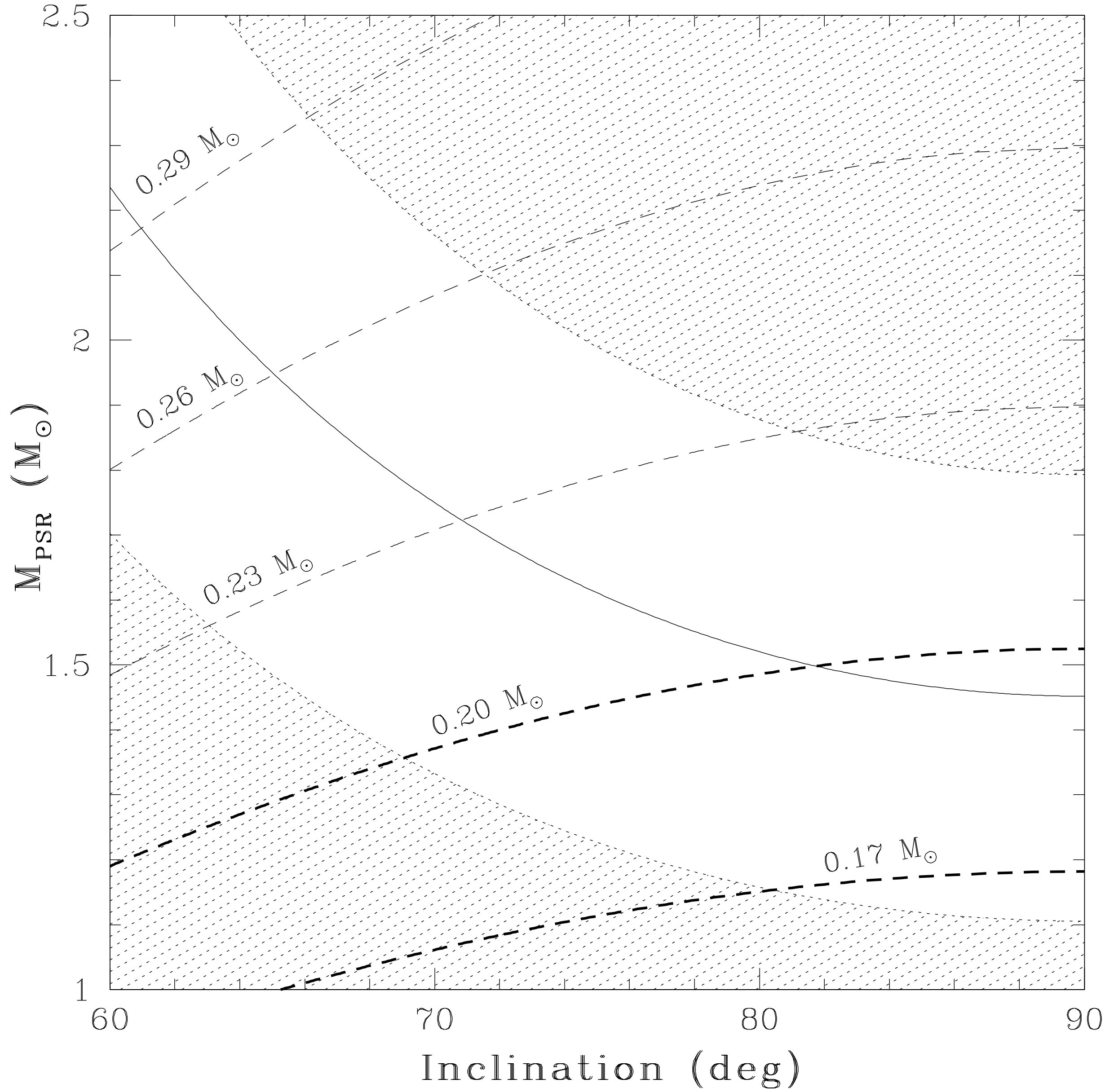

Fig. 2.— Mass of PSR J1911−5958A and orbital inclination of the binary. The allowed range of values are constrained to lie within the strip whose borders (*dotted lines*) are the 1σ boundaries derived from the mass ratio of the system. Lines of constant mass for COM J1911−5958A are also shown (*dashed lines*) and labeled with the assumed mass value. If COM J1911−5958A is a He-WD, the space of parameters is additionally constrained (see Ferraro et al. 2003a) between the lines corresponding to companion masses 0.17 and 0.20 $M_\odot$ (*thick dashed lines*).

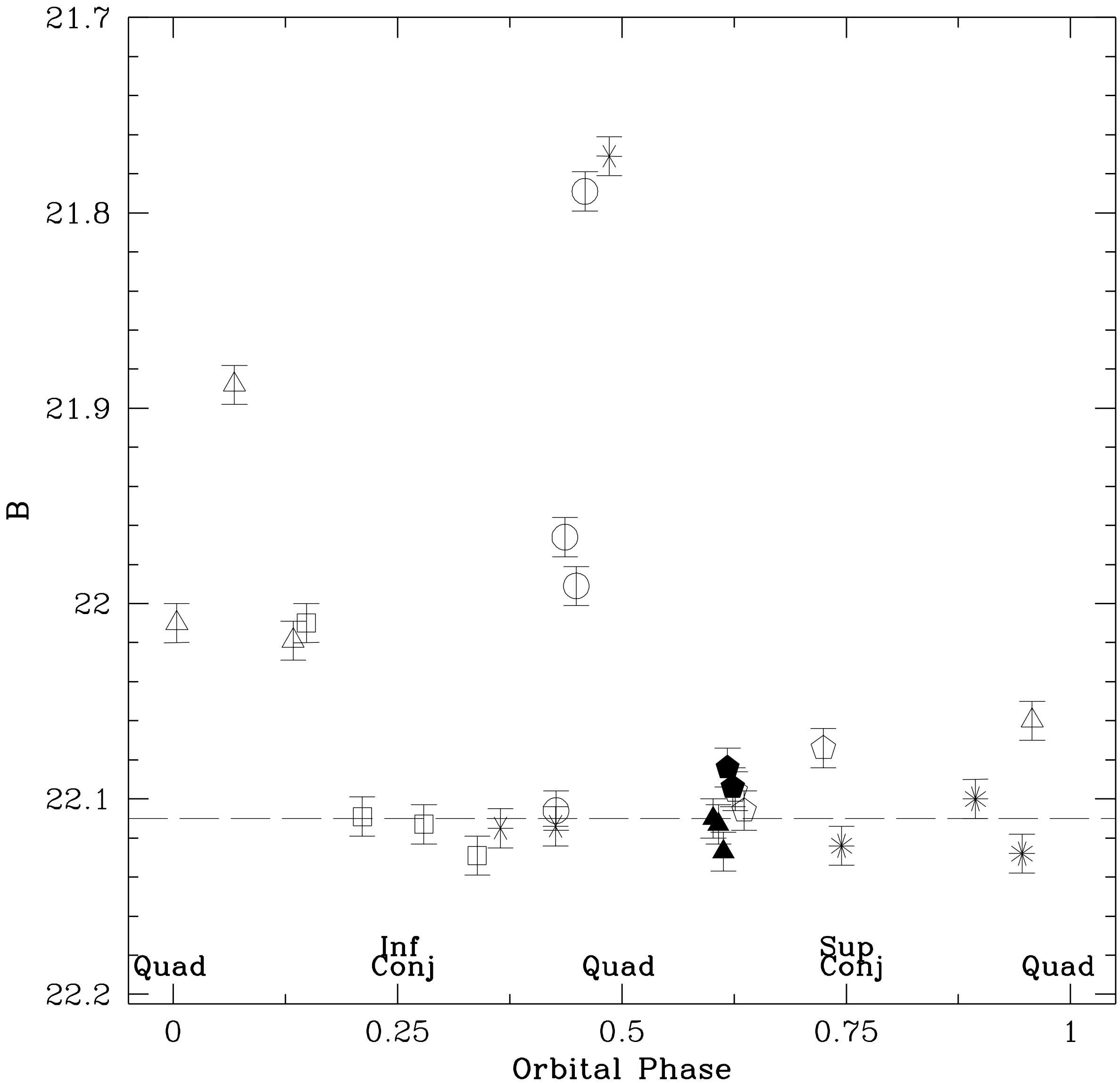

Fig. 3.— Light curve of COM J1911−5958A: the *filled* symbols represent observations performed on two different nights on March and May 2003, whereas the *empty* and *starred* symbols represent the data collected on August 2004. Different marks refer to different nights of observation. The horizontal *dashed line* represents the off-peaks mean B-magnitude of the source, calculated averaging the data at orbital phases in the ranges (0.2−0.4) and (0.6−0.95). The phases of quadrature and conjunction of COM J1911−5958A are reported for clarity.