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The Black-Widow M71A and the dynamical status of its host globular cluster

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Abstract. We present the identification and the characterization of the optical counterpart to the black-widow system J1953+1846A in the globular cluster M71, an ultra-compact binary system which shows periodical eclipses of the radio pulsar signal. The strongly variable light curve of the optically detected companion star clearly shows that this object is interacting with the neutron stars and its global properties and evolution are dominated by the strong irradiation due to the pulsar injected flux. The host globular cluster M71 harbors an anomalously rich X-ray source population. By studying the cluster density profile, we found that the cluster structural parameters are significantly different from those reported in literature, resulting in a collisional encounter rate about twice the previous value. Moreover, by studying the cluster orbit in the Galaxy, we discuss that M71 must have lost a significant fraction of its initial mass, thus explaining its X-ray source overabundance.

Key words. pulsars: individual (PSR J1953+1846A) – globular clusters: individual (M71) – Technique: photometric –Proper motions.

1. Introduction

Due to their high collisional environments, globular clusters (GCs) represent the ideal habitat to the formation of exotic objects such as millisecond pulsars (MSPs): old and fast spinning neutron stars spun up through mass accretion from a companion star. Among MSPs are particularly worth of attention the so-called "spiders": ultra-compact binary systems that show periodical eclipses of the radio pulsar signal, likely due to the presence of ionized material lost by a non-degenerate companion star. They are commonly divided into two classes: Black-Widows (BWs), the ones with very low-mass companion stars ($M_{\rm COM} < 0.1 M_{\odot}$), and Redbacks (RBs), the ones with relatively more massive companion stars ($M_{\rm COM} < 0.5 M_{\odot}$). The identification of the companion stars to these systems, which is possibile only through optical observations, is crucial to get insights on the nature of the secondary star and on the complex physic of these closely interacting binary systems (see Ferraro et al. 2001, 2003a,b; Sabbi et al. 2003; Mucciarelli et al. 2013).

Here we present the optical identification of the MSP J1953+1846A (hereafter M71A), a BW in the GC M71. M71 is a low-density and low-mass GC located at about 4 kpc from the Sun. Elsner et al. (2008) and Huang et al. (2010) showed that this system hosts a large number of X-ray sources (i.e. likely stellarexotica), larger than expected from its collisional parameter and its total stellar mass. In the last section of this work, we discuss the possible reasons behind this overabundance.

2. The Black-Widow M71A

M71A is the only MSP identified so far in the GC M71 (Hessels et al. 2007). It is a binary system with a orbital period of about 4.24 hours and shows eclipses for about 20% of its orbit, during the MSP superior conjunction (Cadelano et al. 2015a). Chandra X-ray observations revealed a X-ray counterpart, whose non-thermal emission is likely the result of intrabinary shocks (Elsner et al. 2008). The position of the BW system is accurately known from radio timing: RA = $19^h53^m46.41966^s$; Dec = $+18°47'04.8472''$.

The Optical Counterpart By using high-resolution observations obtained with the *Hubble Space Telescope* ACS camera (GO1775, GO12932) we identified the optical counterpart of M71A (i.e., its companion star) (see Cadelano et al. 2015a, for the complete discussion). Indeed, a very faint star is located at only $0.06''$ from the radio position. In order to confirm the link between this star and M71A, we built the light curve folding the optical measurements with the radio timing ephemeris. The results are shown in Figure 1, left panel. As can be seen, the light curve shows a strong variability and the star spans about three magnitudes between the minimum and the maximum luminosities. The minimum is located at orbital phase 0.25, thus at the MSP superior conjunction, while the maximum is at orbital phase 0.75, the MSP inferior conjunction, solidly confirming that this star is the optical counterpart to M71A. The light curve structure, with a single minimum and a single maximum, is indicative of a strong irradiation of the companion side directly exposed to the MSP emitted flux. Indeed, at the MSP inferior conjunction, where the maximum luminosity occurs, we can directly see the stellar side exposed to the MSP flux, while at the MSP superior conjunction, where the minimum luminosity occurs, we are observing the back side of the companion star, not directly facing the MSP. In the color-magnitude diagram the companion star is located, during the whole orbit, in a low luminosity region, between the main sequence and the white dwarf cooling sequence (Figure 1, right panel), in a region where normal and unperturbed stars are not expected, thus further confirming that this is a strongly perturbed and non-degenerate object.

The optical counterpart to M71A is the second BW identified in a GC. The first one was M5C, identified by Pallanca et al. (2014) in the GC M5. Both these BWs show a similar light curve structure, with a single minimum and maximum, suggesting that the irradiation is a common phenomenon in shaping BW properties. The two systems also share the same anomalous position in the color-magnitude diagram. Close analogies can be also found not only with other BW systems, but also with RBs. For example, the RB systems 47TucW in the GC 47 Tucanae shows a very similar light curve structure (Edmonds et al. 2002; Cadelano et al. 2015b), thus suggesting that irradiation and thus vaporization of the companion star are key ingredients to understand the properties not only of BWs, but also of at least some RB systems. Again, 47TucW share the same color-magnitude position as M71A and M5C, at odds with what observed for other RB systems (Ferraro et al. 2001; Cocozza et al. 2008; Pallanca et al. 2010).

3. The host globular cluster: M71

In order to understand the X-ray sources overabundance in M71, we analyzed the cluster density profile and its orbit within the Galaxy. All these results will be published in Cadelano et al. (2016, in preparation).

Structural Parameters We used ground based infrared observations obtained with the WirCam camera on the CFHT telescope (Prop ID: 11AD90), from which we obtained a catalogue of the starts of the whole field of view. Then, we determined the cluster density profile by direct stellar counts (see, e.g., Miocchi et

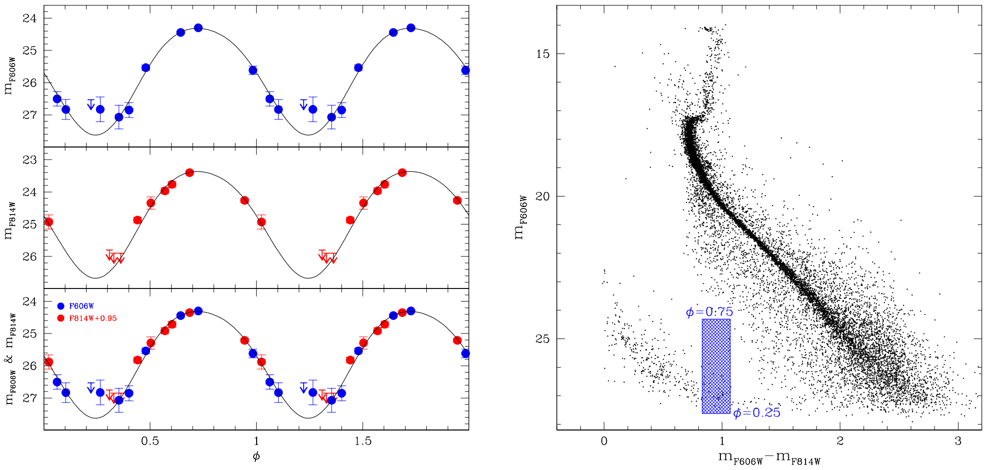

Fig. 1. *Left:* M71A light curve. Points in blue are from F606W filter measurements, while points in red are from F814W data. The black curve represent the best-fit model. *Right:* M71 color-magnitude diagram with the position assumed by the companion to M71A during its whole orbital period marked in blue.

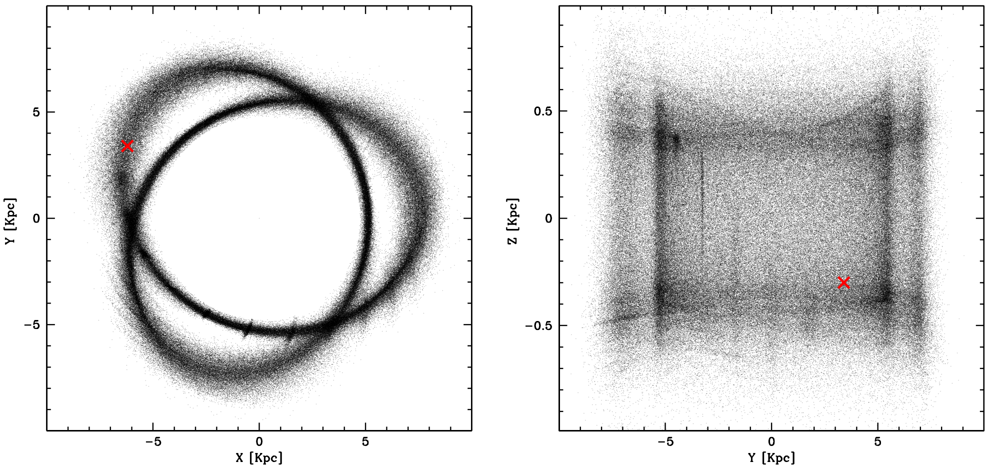

Fig. 2. *Left:* Positions of M71 in the equatorial Galactic plane as obtained from simulations of its orbit during the last 3 Gyr. Each point represents the position of one (out of 1000) cluster in different snapshots obtained during the numerical integration. The red cross marks che current cluster position. *Right:* Same as in the left panel but in the meridional Galactic plane.

al. 2013). The profile has then been fitted with a single mass King model (King 1966) to derive the cluster structural parameters. We have found that M71 has a core radius of 59″, an half-mass radius of 174″ and a concentration of 1.3. Thus the cluster is slightly more concentrated than previously reported in literature and it has a 50% larger core and half-mass radii (compare to the values quoted in Peterson & Reed 1987). This results in a collisional parameter about twice the previous value, which is not large enough to explain the observed X-ray sources overabundance (see Figure 6 in Huang et al. 2010).

Orbit We exploited the same two ACS datasets used for the identification of M71A to determine the stellar proper motions, being the two datasets separated by a temporal baseline of 7 years. We then measured the cluster absolute proper motion in the sky by using six extragalactic objects in the background (see e.g. Dinescu et al. 1999; Bellini et al. 2010). The resulting absolute proper motion of M71 is $(\mu_\alpha \cos\delta, \mu_\delta) = (-2.8 \pm 0.5, -2.3 \pm 0.4)$ mas yr^{-1}. We used this information, together with the cluster radial velocity of -23.1 km s^{-1} (Kimmig et al. 2015) and its current position, to study its orbit within the Galaxy. To this aim, we followed the procedure fully described in Massari et al. (2015), using a three-component Galactic potential model and back-integrating the orbit for 3 Gyr. To take into account uncertainties, we simulated 1000 GCs with initial conditions normally distributed within the proper motion uncertainties. The results are shown in Figure 2. As can be see, M71 persists on a low-latitude orbit within the Galactic disk and outside the bulge, resembling the orbits typically observed for open clusters, in a region where the Galactic tidal field is strong enough to have caused a significant amount of cluster mass loss. Indeed, following a simple recipe by Lamers et al. (2005), and assuming a cluster current mass of $2 \times 10^4 M_\odot$ (Kimmig et al. 2015) and an age of 12 Gyr, we estimate that the initial mass of M71 should have been of about $10^5 M_\odot$, which is the typical mass of a halo GC. This significantly larger initial mass can naturally explain why the number of X-ray sources is larger than expected from the cluster current mass.

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