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Is there a propeller neutron star in γ Cas?

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ABSTRACT

γ Cas is the prototype of a small population of B0-B1.5 III-V classical Be (cBe) stars that emit anomalous and hard X-rays with a unique array of properties. γ Cas is known to host, like other cBe stars, a decretion disc and also a low-mass companion. Recently, Postnov et al. have posited that this companion is a magnetized rapidly spinning neutron star that deflects direct gravitational accretion from a stellar/disc wind via the 'propeller mechanism'. These authors state that the key X-ray observations are 'remarkably well produced' in this scenario. We re-examine this mechanism in detail and conclude that there are a number of fatal objections in its application to the γ Cas case. Among other considerations these issues include the prediction under the propeller scenario of a much smaller population of γ Cas stars than is observed and the lack of allowance for observed correlations of X-ray and UV and/or optical properties over a variety of time-scales.

Key words: accretion, accretion discs – stars: emission-line, Be – stars: individual – stars: massive – stars: neutron – X-rays: stars.

1 INTRODUCTION

Over the last 20 years, we authors have conducted a number of observational campaigns to monitor the properties in the X-ray, optical and ultraviolet domains of the hard X-ray emitter γ Cas (B0.5 IV-Ve). All this work has led us to a picture in which these anomalous X-ray emissions are produced by the interaction of magnetic fields of this star and its Be 'decretion' disc. This holds as well among 'analogue' members of this new X-ray Be subgroup.

In this picture, X-rays are generated from high-energy particle beams directed to the surface of the Be star and depositing their energy as hard X-ray-visible quasi-flares. These beams are created by acceleration of particles situated within the ambient field lines following their entanglement of two magnetic field structures. The first structure consists of local chaotic field lines emanating from and corotating with the star. The second is a toroidal field embedded in the Be star's Keplerian disc and perhaps amplified by the Balbus & Hawley (1991) magnetorotational instability (Robinson, Smith & Henry 2002). Robinson & Smith (2000, 'RS00') reported numerical simulations to show what attributes the high-energy electron beam might have to generate the observed X-ray flux. Of course there is no way to directly observe this complicated interplay. Rather it can be inferred only as a result of employing a variety of observational techniques.

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In a recent paper, Postnov, Oskinova & Torrejón (2017, 'POT17') have proposed instead that the hard X-ray emission from the γ Cas system is caused by the operation of a 'propeller' associated with a rigidly rotating magnetosphere around a *putative neutron star* (NS) secondary. However, this narrative has intrinsic weaknesses and overlooks key observational properties of the Be star and disc. We believe also that the mechanism they propose is inherently untenable for these stars, and we address these issues herein. In doing so, we occasionally draw on additional information known from other analogues of this γ Cas subgroup. Much of this information is taken from a general review paper (Smith, Lopes de Oliveira & Motch 2016, 'SLM16') and references cited therein.

2 X-RAY AND RELATED PROPERTIES OF γ CAS

γ Cas is the prototype of a subgroup of 10–12 Galactic X-ray classical Be stars. Members of this subgroup are confined to the region B0-B1.5, luminosity class III, IV in the HR diagram (SLM16). Radial velocity studies of γ Cas reveal it to be a single-line binary in a wide, circular orbit ($P = 203.59$ d; $e \leq 0.03$; Smith et al. 2012a, 'SLM12a'). The secondary's mass is about 0.8 $\pm$0.4 $M_\odot$. Otherwise, we stress that its evolutionary status is unknown. For example, the secondary could be a late-type main-sequence star or for that matter a passive degenerate star. Long Baseline Optical Interferometry from a number of studies has fixed the obliquity of the Be-disc system to our line of sight as $i \approx 42^\circ$ (SLM12a). The Be component

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of γ Cas has a rotational period of ≈1.22 d (Henry & Smith 2012, 'HS12'). This conclusion comes from a robust periodic feature in its optical light curve and is consistent with the extreme rotational broadening of its spectral lines. Given this period, its estimated radius and sin *i* obliquity, γ Cas appears to rotate nearly at the critical velocity. This rotation could produce localized magnetic dynamo instabilities due to an enhanced equatorial convection zone (Motch, Lopes de Oliveira & Smith 2015, 'MLS15'). This may speak to the cause of the star's role in generating hard X-rays and can address the possible criticism that most other early Be stars with extensive discs do not emit this radiation. Likewise, it is sometimes speculated that γ Cas is in an intermediate state of binary evolution because as many as three members of the subgroup could be blue stragglers in clusters (SLM16).

γ Cas stars are recognizable by their unique array of X-ray emission characteristics among high-mass X-ray stars. The emission is 'hard', and their moderate L_x luminosity, 3–10× 10^{32} erg s^{-1}, (as measured in the 0.1–10 keV X-ray band) is intermediate between so-called classical Be stars and X-ray Be (XRBe) binary systems. High-resolution spectra of γ Cas, which include the continuum and resolve the Lyman α emission lines of Fe XXV (at 6.7 keV) and Fe XXVI (at 6.9 keV), are fit well with an optically thin thermal model described by a 'primary' plasma temperature 'kT_{hot}' ≈14 keV and (usually) an attenuation of soft X-ray flux by photoelectric absorption of 'cold' matter. Importantly, for γ Cas a second (often higher) column density of cold matter is also present in the foreground of the hot primary X-ray plasma. We should note clearly that the flux of the primary component dominates at all X-ray wavelengths (save the wavelengths of soft and moderate energy X-ray lines). It follows that the attenuation of soft X-ray signals the presence of this cold matter along the line of sight to the hot plasma behind it. It remains to be added that fluorescence lines of Fe and Si are present in the γ Cas X-ray spectrum. These features, which change with time, indicate the presence of cold matter close to the hot X-ray sources.

The primary plasma can take on various kT_{hot} values for different members of the γ Cas subgroup. For at least half of those γ Cas stars observed more than once, the primary plasma's temperature has been found to change. In addition, for the best observed stars the presence of emission lines of H- and He-like lines of lower ionization metallic species at lower energies (0.3–0.6 keV band) discloses that 2–3 secondary cooler plasmas are present. These plasmas seem to be monothermal because a model described by a differential emission measure (EM), that is, by a plasma having by a continuous distribution of temperatures, does not give a good fit (Lopes de Oliveira, Smith & Motch 2010; SLM12a).

Although the abundances derived from spectral analysis are generally consistent with solar values, for a few elements their values are non-solar and these abundances vary over time. These include over or underabundances of atomic neon and nitrogen. These anomalies are inconsistent with abundances produced by core or shell burning in late stages of stellar evolution, e.g. of a putative pre-supernova. Curiously, a persistent low iron abundance has been found from the Fe K-shell lines of Fe XXV and Fe XXVI determined by many authors using as many X-ray telescopes, even though the abundance derived from L-shell ion lines is solar like.

The X-ray light curve of γ Cas exhibits an array of variations characterized by certain time-scales. These include (1) ubiquitous 'shots' or quasi-flares lasting a (few seconds to a minute), (2) erratic 'undulations' over tens of minutes to hours, (3) long-cycles (∼70 d) and (4) seemingly chaotic, even longer term variations (MLS15; SLM16). In addition to the 'flares', variations of an underlying 'basal' X-ray flux component can be present. This component constitutes ≈ $\frac{2}{3}$ of the total flux, exhibits the same kT_{hot} as the flares and varies on a time-scale of a few hours (bullet 2). Unlike true magnetic flares in cool stars, the tails of the flare profiles exhibit no tapering or extensions (Smith, Robinson & Corbet 1998a, 'SRC98'). This fact suggests a rapid decay time-scale. In general, the flares are visible in both soft and hard X-ray bandpasses, but exceptions occur in which they are present in one energy band and are weak or absent in the other according to Smith, Lopes de Oliveira & Motch (2012b, 'SLM12b'). This study also found that the flare properties of γ Cas are essentially the same for another γ Cas analogue, HD 110432 (B0.5 IIIe).

Power spectra of the short time-scales (1) and (2) variations describe epoch-dependent, mild deviations from a $1/f^n$ relation (where n is always near unity). However, the details of these relations depend upon an epoch-dependent distribution of flare strengths.

The quasi-sinusoidal ∼70 d cycle was first observed in optical photometry. This cycle is almost ubiquitous and in the X-ray region attain an amplitude of a factor of 2–3. These X-ray variations generally correlate well with optical variations (RS00; HS12; MLS15). The Johnson *V*-band amplitudes of the optical cycles are greater than the *B* ones. This means the only other possible contributor to red-optical flux in the Be complex, the Be decretion disc, must play an important role in the generation of at least the variable component of the hard X-ray flux. This is the primary reason for including the disc in the magnetic interaction picture.

On a time-scale of several months, MLS15 found that optical flux changes caused by density variations in the inner part of the decretion disc are strongly correlated with X-ray fluxes with a similar flux ratio as seen for the 70 d cycles. They found that optical and X-ray fluxes vary together with a time delay of less than one month. These authors have also shown that such a small time lag is inconsistent with the expected transit time from inner disc regions to the orbit of the companion.

For completion, we note that UV light curves of γ Cas exhibit small dips lasting a few hours, and optical helium line profiles exhibit blue to red rapidly moving migrating subfeatures (Smith, Robinson & Hatzes 1998b). Neither of these signatures is correlated with the star's X-ray flux, though both indicate the presence of plasma forced into corotation just over the star's surface.

Apart from the hard flux variations, the soft relative to hard energy flux can change on time-scales of 10 d or longer (SLM12a), and at times rapidly over several minutes (Hamaguchi et al. 2016). This is the 'attenuation effect' noted above. The occurrence of this effect is important because it conveys important geometrical details of the hard X-ray sources. In this case, SLM12a noted that the presence of intervening cold matter indicates no relation with binary phase of γ Cas during an outburst event in 2010. Significantly, the cold matter absorption column increased simultaneously with the beginning of the 2010 Be outburst, which is to say the ejection of matter from the Be star. The occurrence of this column of the cold matter places the hot, high plasma density, X-ray sources between observer and the Be star. We develop this point below.

A particularly salient discovery concerning the hard X-ray flux is the tight relation between its variations and ultraviolet line strengths and continuum, and optical light curves (SLM16 and references cited therein). For example, from a 21-h simultaneous monitoring in 1996 of γ Cas by the *Rossi X-ray Telescope Explorer (RXTE)* and the *Goddard High Resolution Spectrograph* attached to the *Hubble Space Telescope,* Smith & Robinson (2003) reported that increases in X-ray flux were associated with strengthening of a UV Fe V line and weakening of UV Si III lines on time-scales of several minutes. This behaviour is consistent only with plasma near a bright and optically thick medium, namely when the UV line strengths increase or decrease in response to a nearby X-ray source. These relationships constitute a particularly critical argument in locating the X-ray plasma near the Be star.

We underscore that observations reported in many studies of early-B/degenerate star binaries at large disclose that ultraviolet light from the secondary component is not visible against the primary's contribution. Even for systems with hot degenerate secondaries essentially all the UV flux comes from the B star. Also, while initial hydrodynamical simulations suggest that the discs are likely to be truncated by 3:1 orbital tidal resonances (Okazaki & Negueruela 2001), the actual mass transfer rate deposited to the secondary (whether degenerate or otherwise) is unknown.

3 PROPERTIES OF X PER

In the POT17 scenario γ Cas can evolve to become an X Per-like object. Therefore, we summarize the relevant attributes of this well-known system. The Be binary X-ray pulsar X Per/4U 352+309 consists of an O9 III primary star and X-ray pulsing ($P_{\rm puls} \sim 837$ s) NS. As summarized by Lutovinov, Tsygankov & Chernyakova (2012, 'LTC12'), the system has a low/intermediate orbital eccentricity $e = 0.11$ and $P_{\rm orb} = 250$ d. The X-ray luminosity (0.1–10 keV) at its usual low state is about 2×10^{34} erg s^{-1}. LTC12 found that during one of its X-ray outbursts its X-ray flux increased and then subsided by a factor of 5. The rise and decline each lasted a year or so while its optical light curve showed little or no response. As already noted, in contrast the largest X-ray variations of γ Cas occur in the form of its rapid 'flares'. Its longer term variations do not exceed a factor of 2–3 at most, and these are correlated with optical flux. X Per is the prototype of a small group of 'persistent' Be slow X-ray pulsar systems. These persistent systems are generally thought to be products of 'low kick' orbital perturbations resulting from a mild supernova (SN) explosion.

The X-ray emissions from a Be–NS system are determined by details of a wind flow from the Be star (or its disc) to a magnetized NS companion.[1] Magnetic field strengths of these pulsars are estimated to be of the order of 10^{12} G or even higher. Particles from the wind are ultimately deposited on to the surface of a magnetosphere (defined below), where they are guided into columns by the pulsar's field towards its magnetic poles. We observe the X-ray emission along these columns as *pulses* because the poles are rotationally advected across our line of sight. The resulting spectrum is typically optically thick. In the case of X Per, the spectrum can be fit well at high energies with a hard power law (index $n \approx 2$) and at low energies by a relatively cool blackbody (e.g. LTC12). These attributes are very different from those in the γ Cas spectrum.

4 THE PROPELLER MECHANISM

In describing the geometry of particle accretion on to X-ray pulsars, we should first summarize the properties of three characteristic radii of volumes around the NS. The first is the well-known Bondi–Hoyle radius, $R_{\rm B}$, within which wind particles from the Be star or its disc spiral towards the NS due to gravitation. They will deposit their energy on the star's surface as X-rays or in its magnetosphere if the NS is highly magnetic.

The second important size is of the magnetosphere, given by the Alfvén radius $R_{\rm A}$. This is the distance from the NS for which the decreasing magnetic pressure is balanced by the ambient ram pressure from the wind. Inside this radius, the magnetic pressure wins and so the magnetosphere rotates rigidly with the NS and carries along embedded plasma. In the simple dipole case, captured wind particles flow mainly towards the magnetic poles.

The remaining important radius is the corotation radius, $R_{\rm C}$, which is the point at which the angular velocity of particles orbiting the star equals the NS rotational value. Inflowing magnetically channelled wind particles just beyond this radius are super-Keplerian and spiral outward to a larger orbit.

For typical Be–magnetic NS systems, the Alfvén radius lies *interior* to the corotation radius. This permits wind particles to freely transit from their origin to the rotating magnetosphere and be captured by magnetic stresses at its surface. The kinetic energy of the particles is transformed chiefly to X-rays, which typically display a power-law (non-thermal) spectrum. The particles are channelled along magnetic flux lines towards the NS. The luminosity $L_{\rm x}$ depends in part on the accretion radius, which in this case is the much larger Bondi radius, $R_{\rm B}$.

For the case of γ Cas, POT17 have considered an alternative propeller regime, for which $R_{\rm C} < R_{\rm A}$, which may occur for fast rotating pulsars. In this configuration, the rigidly rotating magnetosphere extends to a region where wind particle velocities are super-Keplerian, they can fall no further than the magnetosphere's boundary. The centrifugal forces at the surface of the magnetosphere prevent particle accretion such that most of them are deflected outwards. They subsequently accumulate within a shell bounded by $R_{\rm A} < r < R_{\rm B}$, with most of them concentrated at the inner boundary. The particles are then pushed by the upstream ram pressure of the wind deep into the magnetosphere. The surface shell remains optically thin and so it emits little UV or optical flux. The accretion radius (and hence $L_{\rm x}$) and temperature of the heated plasma are now partly determined by $R_{\rm A}$, which in turn is much smaller than $R_{\rm B}$. Note that a substantial X-ray luminosity and hard spectrum can result. A number of papers in the literature have suggested that the outburst or high state of short period XRBe systems occurs when the propeller mechanism temporarily ceases to operate and uninhibited accretion resumes (see e.g. Christodoulou et al. 2016; Reig & Milonaki 2016; Tsygankov et al. 2016, and references therein). These outburst events occur on short time-scales, at least in part as response to surges in wind density, leading to brief outbursts from direct accretion. Since $R_{\rm A}$ shrinks in response to increases in accretion density, the inequality is reversed, that is $R_{\rm A} < R_{\rm C}$, during these outbursts. Again, this outburst behaviour is in contrast to long-term changes in the accretion phase forced by NS spin-down and binary evolution. These evolutionary considerations are discussed in the next section.

5 EVOLUTIONARY TIME-SCALES

The POT17 proposal merges the above ideas into a putatively integrated evolutionary scenario. These authors pictured γ Cas as a progenitor of a class of low to moderate eccentricity XRBe systems such as X Per. In their description of the γ Cas system, the putative fast rotating NS is in the propeller mode and gradually loses rotational energy owing to a braking torque of the surrounding magnetosphere. This torque acts from radiative losses and mechanical drag on the rotating magnetosphere by the wind. As the rotational angular velocity of the NS slows, the corotation radius $R_{\rm C}$

[1] We use the term 'wind' throughout, in the understanding that the outflow may not be due to the usual line-driven radiative wind occurring in most OB stars (see e.g. Carciofi et al. 2012).

increases, moves outside R_A, and direct accretion via gravitation can start. POT17 estimated that the propeller phase could last 'several 10^5 yr or even longer'. Next POT17 advanced several predictions to adduce the applicability of their picture.

We will comment on the POT17 predictions and as well as on the applicability of their scheme in Section 6. We review first the durations of the so-called ejector and propeller phases of the magnetic NS. These durations determine the sizes of the population of γ Cas-type systems, which one can compare with the number of known systems in our Galactic neighbourhoods. In Section 5.2, we will present a more complete evolutionary scheme than did POT17 for the transfer of wind particles to the putative NS.

Our scheme has the sequence:

ejector → propeller → direct accretion → spin equilibrium.

The ejector phase will be discussed in Section 5.2.1. As implied, 'direct accretion' here simply refers to the flow of wind particles to the surface of the NS in the case of no (or weak) magnetic field; as noted by POT17 the resulting L_x can be very high because the full gravitational energy of the former wind particles is liberated near the small NS radius. Spin equilibrium, which perhaps should be more accurately called a 'quasi-equilibrium', occurs when the Keplerian orbital velocity of the outer edge of the magnetospheric disc equals the corotation velocity at that point, as defined by Waters & van Kerkwijk (1989). The X-ray source then resides on the Corbet relation for XRBe systems (Corbet 1984). Also note that if the accretion rate changes rapidly, the NS system can transition back and forth between the propeller and ejector modes on short time-scales.

5.1 The velocity of the accreted material

The mass accretion rate required to feed the NS in the propeller mode constrains the possible range of velocities of the accreted material at the Bondi radius. Importantly, as noted by POT17 the duration of the propeller phase critically depends on this velocity.

According to equation 15 of POT17, the mass accretion rate required to sustain an X-ray luminosity of $L_{32} \times 10^{32}$ erg s^{-1} on an NS in propeller mode is

$$\dot{M}_{\rm x} \approx 8.3 \times 10^{-11} \mu_{30}^{2/15} L_{32}^{4/5}\,{\rm M_\odot\,yr^{-1}}, \qquad (1)$$

where μ_{30} [which is $\mu/(10^{30}\,{\rm G\,cm^3})$], the typical dipole magnetic moment of the NS, is approximately unity, and assuming that the mass of the NS, M_x is 1.4 M$_\odot$. The latter is larger than the 1.0 M$_\odot$ value taken by POT17 and is a more realistic value, as noted below; see also Özel et al. (2012) and Özel & Freire (2016). Since accretion occurs through wind capture, $\dot{M}_x$ is the Bondi accretion rate and $\dot{M}_{\rm x} = \pi\rho(r)V_{\rm o}\, R_{\rm B}^2$, with the Bondi radius expressed as $R_{\rm B} = 2\,GM_{\rm X}/V_{\rm o}^2$. Here, we have retained the POT17 notation for parameters. This includes V_o for the vectorial sum of the wind and orbital velocities to which should be quadratically added the sound speed in the accreted material $\approx 10 \times (T/10^4{\rm K})^{1/2}$ km s^{-1}. Our notation for parameters of the Be star will be an asterisk.

Assuming that the NS accretes matter from the intermediate latitude wind that is typical of an early B star, we can relate the mass accretion rate on to the NS to the total mass-loss of the Be star. With $M_* = 15\,{\rm M_\odot}$; $M_{\rm x} = 1.4\,{\rm M_\odot}$ and $P_{\rm orb} = 203.59$ d, M_*, the total mass-loss rate of the primary wind, should be

$$\dot{M}_* = 1.2 \times 10^{-4} \left(\frac{V_{\rm o}}{1000\,{\rm km\,s^{-1}}}\right)^4 {\rm M_\odot\,yr^{-1}}, \qquad (2)$$

which is a few orders of magnitude above the total wind mass-loss rate expected for a B0 IV star, $\dot{M}_* \sim 10^{-8}\,{\rm M_\odot\,yr^{-1}}$.

From the foregoing, one can see that in order to capture enough material the orbit of the NS has to be nearly coplanar with the plane of the decretion disc and accrete low relative velocity and high-density matter. The fraction of observed Be-shell stars led Porter (1996) to conclude that the disc opening angle is typically ≈5 deg, although disc flaring at large radii may weaken this constraint.

The range of observationally permitted orbital inclinations depends on the assumed masses of the B0 star and NS. Assuming the values given above for the primary and secondary stars, combined with the observed radial velocity semi-amplitude of 3.8 km s^{-1} (SLM12a), implies a low orbital inclination of the order of $i \approx 29°$, which is at variance with that of the decretion disc ($i = 42°$) derived from optical interferometry (SLM12a). Such a significant misalignment of the NS orbit with the disc plane can be expected to drive an X-ray flux modulation at the orbital period.

POT17 argue that the helium star electron capture channel could yield NSs with masses as low as 1 M$_\odot$. In this case, a primary with a somewhat high mass of 16 M$_\odot$ would indeed allow a 1 M$_\odot$ mass NS (their assumed mass values) to orbit close to the plane of the decretion disc. However, there is no observational evidence of such low-mass (≲1 M$_\odot$) neutron stars. Although rather few reliable NS mass estimates exist for Be/X-ray systems, not to mention γ Cas-like systems, masses of the non-recycled NS+WD or NS+NS binaries – descendent of these systems – do not show evidence of a significant population of low-mass NSs (see e.g. Özel & Freire 2016). In addition, the amount of accreted matter during the putative X-ray active stage of a few 10^6 yr is only 10^{-3} M$_\odot$ at most. Therefore, we will take the mass of the NS as constant over the entire period.

Optical spectroscopic observations of Be stars have established that the decretion disc is essentially Keplerian, with no detectable outflow velocity (see e.g. Stee et al. 2012, and references therein). As already noted, in low-eccentricity Be/X-ray binary systems such as γ Cas, the disc is very efficiently truncated at the 3:1 resonance radius, leaving a wide gap size between the edge of the disc and the NS (Okazaki & Negueruela 2001; Okazaki, private communication, 2011). Additional numerical simulations by Okazaki & Negueruela (2001) suggest that the infalling disc matter acquires velocities relative to the NS comparable to the sound speed and are at most of the order of a few tens of km s^{-1}. For these velocities, the Bondi accretion radius is comparable to the radius of the Roche lobe. At the distance of the Roche radius of the accreting object in γ Cas, the free-fall velocity is ≈80 km s^{-1}. Whatever the range of primary and secondary masses considered, the orbital velocity of the accreting object remains at nearly similar values of the order of 80–90 km s^{-1} for low eccentricities. It is therefore unlikely that the V_0 velocity in equation 14 of POT17 reaches values much above 100 km s^{-1}. Accordingly, durations of the propeller phase in excess of a few 10^5 yr are very unlikely.

5.2 Spin period evolution

5.2.1 *Ejector phase*

The very first phase of the NS history is the so-called ejector phase during which the ram pressure of the wind entering the gravitational influence of the NS at the Bondi radius is lower than the outgoing flux of electromagnetic waves and relativistic particles emitted by the magnetic NS (pulsar) (see e.g. Popov & Turolla 2012, 'PT12'). This condition is expressed as $P_{\rm dyn} \le P_{\rm PSR}$, with $P_{\rm dyn} = \rho(r)V_{\rm o}^2$ and

$P_{\rm PSR} = \dot{E}/(4\pi R c)$. The power radiated by the slowing down pulsar due to dipole radiation is

$$\dot{E} = 8\pi^4 B^2 R_{\rm ns}^6 \sin^2\alpha/(3c^2 P^4), \quad (3)$$

where B is the magnetic polar dipole field, $R_{\rm X}$, the radius of the NS and α the inclination of the magnetic dipole from the rotation axis.

When does this ejector phase end? This question can be addressed by first assuming the POT17-adopted values of density and velocity for the incoming matter at the Bondi radius sufficient to explain the observed X-ray luminosity in the propeller mode (equation 1), and also by using PT12's equation (1). We can then determine the spin period $P_{\rm ee}$ at which the ejector mode ends. This is

$$P_{\rm ee} \approx 0.48 \times \left(\frac{V_{\rm o}}{100\,{\rm km\,s^{-1}}}\right)^{-1/4} \left(\frac{B}{10^{12}}\right)^{1/2} L_{32}^{-1/5}\ {\rm s}, \quad (4)$$

assuming $M_{\rm x} = 1.4\,{\rm M}_{\odot}$ and $\alpha = 90$ deg.

Next, following PT12, and assuming a canonical moment of inertia $I = 2/5MR^2$ equal to 10^{45} g cm^2, the duration of the ejector phase may be computed as

$$\tau_{\rm ej} \approx 3.6 \times \left(\frac{V_{\rm o}}{100\,{\rm km\,s^{-1}}}\right)^{-1/2} \left(\frac{B}{10^{12}}\right)^{-1} L_{32}^{-2/5}\ {\rm Myr}. \quad (5)$$

Assuming factors of order unity for parameters in equation (5), $\tau_{\rm ej}$ should be a few million years. In addition, the putative NS should have spun-down already significantly during the ejector phase.

5.2.2 *Propeller phase*

As implied in Section 4, the end of the propeller accretion mode occurs when the corotation radius, ever increasing because of NS spin-down, reaches value close to the magnetosphere radius. Using equation 7 of POT17 for the magnetosphere radius and assuming a 1.4 M$_{\odot}$ NS implies that the high X-ray luminosity accretion mode switches on as soon as the spin period becomes longer than

$$P_{\rm ep} = 8.6 \times \mu_{30}^{4/5} L_{32}^{-1/5}\ {\rm s}. \quad (6)$$

The braking torque acting on the NS in the propeller mode is given by equation 12 in POT17. Importantly, the torque is constant and does not depend on the difference between the critical and actual angular frequencies. Accordingly, the duration of the propeller phase is of the order of $\tau_{\rm prop} = 2\pi(1/P_{\rm ep} - 1/P_{\rm ee})/\dot{\omega}$, with

$$\dot{\omega} = -49\, I^{-1}\omega_{\rm B}^2 r_{\rm B}^3 C \frac{R_{\rm A} L_{\rm X}}{G M_{\rm X} V_{\rm o}}, \quad (7)$$

with $\omega_{\rm B}$ the orbital angular frequency and $R_{\rm A}$ the magnetosphere radius. The duration of the propeller phase is given by POT17 in their equation 14. It should be reiterated that some significant spin-down will have occurred during the relatively long ejector phase. Here, we use $P_* = 0.48$ s as derived in our equation (4), a value much longer than the probable birth spin period. Importantly, this significantly further shortens the duration of the propeller phase. Using the Alfvén radius in their equation 7, an average X-ray luminosity of 5×10^{32} erg s^{-1} (SLM16) and $P_{\rm orb} = 203.5$ d, we can express the actual duration of the propeller phase as

$$\tau_{\rm prop} \approx 5 \times 10^5 \left(\frac{V_{\rm o}}{100\,{\rm km\,s^{-1}}}\right)^7\ {\rm yr}. \quad (8)$$

Note that this time-scale is consistent with our estimate in Section 5.1, based on the range of velocities discussed there, and that it is several times shorter than the duration of the ejector phase given in equation (5).

6 OUR VERDICT: NO PROPELLER FOR γ CAS

6.1 Propeller systems in context of Be/X-ray binary evolution

Several independent evolutionary arguments just discussed suggest that the propeller mechanism as proposed by POT17 cannot account for the space density of the γ Cas X-ray phenomenon.

First, as noted in Section 5.1 the velocity of the accreted material at the Bondi radius is unlikely to be much greater than $\approx$100 km s^{-1}. As we have seen, the velocity of the dense flow extracted from the outer edge of the decretion disc probably does not reach values larger than a few tens of km s^{-1}. In addition, we have shown that a large part of the NS spin-down may have already occurred during the ejector phase. From these considerations, one can see that both parameters P_* and $V_{\rm o}$ in equation 14 of POT17 probably have values consistent with a propeller phase duration of only of the order of a few 10^5 yr. It seems clear that the steep dependence of $T_{\rm prop}$ on relative velocity disallows the conclusion that the duration of the propeller phase can be as high as 1 Myr. Secondly, although there may be a few systems in the propeller phase, we consider it unlikely that a large population of NS/γ Cas-like propeller systems exists in the Galaxy. This is because of the rather short duration of the propeller phase. We develop this point in the following.

Over 100 High mass X-ray Be (XMXBe) are known in the Galaxy, among which $\approx$80 per cent are confirmed or candidate Be/X-ray systems (Liu, van Paradijs & Van den Heuvel 2006; Reig 2011). XMXBe population models, e.g. by Portegies Zwart & Verbunt (1996, 'PV96') and Shao & Li (2014, 'SL14'), predict the existence of $\approx$500 Be/X-ray binaries in the Galaxy – a figure roughly consistent with the number of systems known, taking into account observational biases. With a formation rate of $\approx 5 \times 10^5$ yr^{-1}, including effects of NS birth kicks, the lifetime of X-ray Be systems is of the order of $\approx$10 Myr (PV96).

Given the observed long Be/X-ray phase, comparable to the evolutionary time-scale of an early-type mass donor star, the number of progenitors of putative γ Cas propellers cannot be much higher than that of directly accreting systems. Consider therefore the following contradiction. Apart from a handful of nearby systems detected in low-sensitivity all-sky surveys (*HEAO-A1* and *Rosat* all-sky), the great majority of γ Cas-like systems were discovered in *XMM–Newton* galactic surveys (SLM12a). Only a few per cent of the Galaxy have been observed by *XMM–Newton*, and fewer still have been followed up in optical spectroscopy. Nebot et al. (2013) report the discovery of four new γ Cas-like objects at distances of $\approx$2 kpc in a 4 deg ^{2} survey. Taken at face value, and even considering larger errors, this implies the presence of several thousand γ Cas-like objects in the Galaxy, a figure much larger than the 500 members predicted by PV96 and SL14 for the entire set of Galactic Be/X-ray binaries.

Conversely, one may compare the frequency of systems in the ejector phase to systems in the propeller phase. Collision of the relativistic pulsar wind with the stellar wind generates copious high-energy emission across the X-ray to the γ-ray regime (see e.g. Bogovalov et al. 2008). The spectral energy distribution of the binary Be/radio pulsar binary PSR B1259−63 (so far the only one known) peaks in the 10–100 MeV energy range and extends up to more than 100 GeV (Abdo et al. 2011). Dubus (2013, 'D13') convincingly argues that most γ-ray binaries are made of young radio pulsars embedded in the circumstellar material of a massive star. Only pulsars with spin-down luminosities above 10^{35} erg s^{-1} are energetic enough to produce γ-rays, implying γ-ray lifetimes of the order of 6×10^5 yr (D13).[2] Even given the attendant observational biases, the low observed frequency of Galactic γ-ray binaries (only this one Be/NS binary is known in the γ-ray active ejector state) is consistent with the population of their wind-accreting XRBe binary descendants. This provides further support for the conclusion that the propeller mechanism is unable to explain the number of γ Cas stars observed.

POT17 further assume that all γ Cas-like systems must have a low eccentricity, due to the low kick velocity imparted by the particular SN mechanism assumed. However, there is no evidence for such a large population of systems existing before the propeller phase (ejectors), nor afterwards (classical Be/X-ray binaries). In particular, all γ-ray ejector binaries have very eccentric orbits ($e \geq 0.35$, including PSR B1259−69). In addition, all young radio pulsars in binaries with massive companions that have terminated their γ-ray active phase but are still in the ejector phase also have very high eccentricities [$e \geq 0.58$; Manchester (2005, ‘M05’); D13] and spin-down times ($\tau_{\rm sd} \approx 3$–5 Myr; M05), very consistent with the duration of the ejector phase computed in equation (5). The range of eccentricities observed in post-SN systems is consistent with that observed in Be/X-ray binaries in which the vast majority of the systems have eccentricities $\geq$0.3 (Reig 2011). In addition, the great majority of Be slow pulsar systems like X Per have non-circular orbits. Indeed, in the sample of eight long-period pulsar systems identified by Knigge, Coe & Podsladlowski (2012) none is in an almost circular ($e \leq 0.03$) orbit. If such systems are in non-circular orbits, while γ Cas is not, then these two types of systems would appear to be members of two distinct populations.

Apart from the γ Cas stars, there is no reason why a long-lived propeller stage *could not* exist in Be-NS binaries with larger eccentricities or inclined orbits as progenitors of the bulk of Be/X-ray systems.

6.2 Our primary non-evolutionary objections to the Postnov et al. scenario

POT17 do not address the critical details of the optical–UV–X-ray variations or of the X-ray flares. In fact, references in their paper to ‘ultraviolet’ or ‘spectroscopic variations’ were not made and apparently not considered. As outlined above, the correlation and anticorrelation of various UV spectral lines and UV continuum with X-ray variations mean that the X-ray emitting plasma is strongly influenced by the only nearby major source of UV and optical wavelength flux, the Be star. POT17’s overlooking of this fact is our first major objection, apart from evolutionary issues just discussed.

Secondly, the POT17 description of what we call flares (or ‘shots’) was characterized as merely the short time-scale end of a continuous distribution of variabilities. In fact, the short flare decay rates are critical to a more focused consideration as they necessarily imply particle densities of up to 10^{15} cm^{-3} for the pre-flare parcels (SRC98). Such high densities are hardly characteristic of POT17’s hot shell but they *are* characteristic of the Be star’s lower atmosphere, and realistically only of this site. In so far as these observations are not addressed, the POT17 picture is lacking.

Thirdly, the correlation of optical and X-ray ∼70 d cycles mentioned above for γ Cas has important implications. The existence of the red-tinged optical variation implies oscillations with a source that is cooler than the surface of the Be star yet still competing in its optical radiation with the Be star. The inner part of the decretion disc alone qualifies as the secondary source of red-optical light. This means the dense inner region of the disc must somehow be associated with the creation of most or all of the hard X-ray flux.

Fourthly, in 2010 the soft-X-ray flux of γ Cas decreased relative to its hard flux. This occurred during a 44 d monitoring period that coincided with an optical outburst. This event added matter to the line-of-sight column density. In other words, the hard X-ray source (which produces most of the soft X-ray flux as well) must lie close to the outbursting Be star. We stress here that the hot sources cannot be placed anywhere else but on the surface of the Be star – for example, in the inner disc as the density is too low to be consistent with the short flare decays mentioned above.

Fifthly, POT17 claimed the prediction of a 40-d time lag of X-ray behind optical signal and cited an MLS15 result as confirmation. This is a misreading. First, MLS15 found no lag at all. The ‘one month’ figure MLS15 quote refers to a generous upper limit, not an equality. Secondly, the optical/X-ray time for any lag in Be-NS X-ray systems is not only the free-fall time into the NS potential well but must also include the transit times from the stellar ejection and transits through the Be disc and to the secondary companion. One must look to actual empirical examples of a transit time. A literature search for such correlated outbursts by MLS15 reveals two cases of optical–X-ray lag (one of them is X Per itself). The optical/X-ray lags in these cases, that is from the Be outburst to a response at the NS, have been observed to be about 4 yr in both cases, (e.g. Carciofi et al. 2012; Haubois et al. 2012). Thus, this is the lag time-scale one can expect under the POT17 or other accretion scenarios. It is in disagreement with the observational result of MLS15, which again points to the X-ray emission of γ Cas arising from the vicinity of the Be star.

Any one of these arguments is sufficient to vitiate, or at the very least seriously question, whether the propeller mechanism is applicable to the γ Cas stars.

6.3 Other criticisms of the Postnov et al. scenario

To complement the foregoing, we rebut purported predictions made by POT17.

(i) The propeller/hot shell picture predicts a continuous range of temperatures for the heated plasma from an initial high value, $kT_{\rm hot}$ (POT17, equation 3). Although we do not understand ourselves, the origin of the secondary plasma components surrounding γ Cas, the evidence for their existence as discrete structures (e.g. SLM12a; SLM12b), contradicts the finding by POT17 that the temperature distribution should be continuous.

(ii) The value of $kT_{\rm hot}$ derived by POT17 for the magnetosphere base is quoted as ≈27–32 keV. Since this figure is actually based on a selection of particular NS mass and radius values by the authors among a range of possible values, it is not necessarily a prediction. The stated temperature also depends upon the unknown mass flow rate impacting the Bondi sphere. Moreover, although a field strength of 10^{12} G is generally quoted, the dispersion of these strengths among X Per-like pulsars is not well known. Given these

[2] However, even for these systems the NS star remains γ-ray quiet during the ejector phase.

uncertainties, we doubt that the temperature according to their propeller model can be reliably predicted.

(iii) Similarly, we note that two propeller systems, 4U 01165+63 and V 0332+53, that have been caught transitioning from a non-propeller to propeller phase, exhibit soft, not hard, X-ray spectra during the latter phase (Tsygankov et al. 2016). This is obviously contrary to expectation from the POT17 model.

(iv) POT17 discuss a 'continuous' distribution of variability time-scales from several seconds to a few days in γ Cas's X-ray light curve. However, this is somewhat misleading. Although periodograms of X-ray variations for γ Cas indeed vary monotonically over these time-scales, a detailed inspection of several data series reveals departures from a simple or smooth frequency pattern, and the degree of these departures varies from epoch to epoch (e.g. RS00). Importantly, POT17's discussion implies that the rapid variations are part of a chaotic pattern of variations. This characterization is in stark contrast to their character as isolated, plainly visible sharp features in all high-resolution time series. As noted already, for time-scales >1 d there is also a significant peak due to the ∼70 d cycles in the low-frequency region of the periodogram, Additional signal extends up to about one year.

(v) POT17 estimate an EM of $\approx 3.7 \times 10^{54}$ cm^{-3} for γ Cas from their model. Without indicating whether more optimistic selections of parameters are still reasonable, they added that the EM can be some 10 times higher. Available spectroscopic analyses of γ Cas indicate EM values of up to 3×10^{55} cm^{-3} (S04; SLM12a), or 10 times above the best POT17 model. Similar values are obtained for HD 110432 (Lopes de Oliveira et al. 2010, 'LSM10'; Torrejón et al. 2012).

(vi) POT17 estimated the convective velocity of 1000 km s^{-1} in their hot shell and they averred this to be an important prediction of X-ray line broadening. Actually, typical turbulence values measured in lines in high-resolution X-ray spectra of γ Cas are 300–500 km s^{-1} (S04 and SLM12a). POT17 overlooked these findings. The signal-to-noise ratio in Fe lines is generally too poor to make a reliable determination (LSM10), and interpretational issues occur for these lines as well. Also, SRC98 showed that velocities of $\gtrsim$1300 km s^{-1} (the expulsion as well as thermal velocity) could be predicted in their description of exploding surface flare parcels.

(vii) POT17 state that the observation of the Fe fluorescent feature is another prediction of their picture. However, such features are present in many types of X-ray binary systems, regardless of the status of a degenerate companion and X-ray generation process.

(viii) An important characteristic of the POT17 model is that the orbital and Be disc planes are aligned. As noted in Section 5.1, a significant tilt of the orbital plane would cause an X-ray flux modulation. Such a modulation is not seen (MLS15). Even a small kick may well move the NS out from its former orbital plane. Note that there is no reason why a kick experienced by an NS explosion should be directed within the orbital plane. Since the POT17 hypothesis requires that *all* γ Cas systems have propellers, it follows that the kicks of all of them be confined to their NS's equatorial planes. This would be a highly unlikely series of events.

(ix) A salient feature of γ Cas-like stars is their narrow range of X-ray luminosities. This would imply in the Postnov et al. scenario that in all γ Cas systems, the NS should orbit at nearly the same distance from the Be star. Their decretion discs should also have similar extents and densities. We have already discussed that the improbable small ranges in orbital eccentricity and inclination are implied.

(x) In the HR diagram, the γ Cas stars are confined approximately to spectral types B0-B1.5 and luminosity classes III-V. One can expect their progenitors on the zero age main sequence to be late-type O stars. However, the domain of the persistent XRBe NS systems is somewhat larger. The persistent systems could not be expected to evolve to as narrow a spectral type domain as the γ Cas stars occupy.

7 FINAL CONSIDERATIONS

In contrast to the propeller mechanism proposed by POT17, RS00, SLM16 and other studies cited therein have led to the interpretation that the generation of hard X-rays from γ Cas are caused by an interaction of magnetic fields from the Be star and its decretion disc. Our initial picture has evolved with the accumulation of new data sets and is particularly informed by analyses of data from a number of multiwavelength observational campaigns. As noted, the light curves and spectra we analysed consist of simultaneous X-ray/UV from the 1996 campaign, as well as some 19 seasons of robotic two-colour Automated Photometric Telescope (robotic) photometry, most of which were contemporaneous with X-ray monitorings. The latter include the long-term *RXTE* all sky monitor programme. An assessment of these combined data sets demonstrates that it is futile to construct *any* paradigm for the origin of the hard X-ray that does not include detailed analysis of concomitant optical and UV variations.

As noted by POT17, no magnetic signatures have been reported by spectropolarimetry in γ Cas. It is very difficult to detect spectropolarization signatures in the very broadened lines of this star. Moreover, polarimetric techniques are tailored to the detection of magnetic dipoles, and other aspects of the star's behaviour strongly suggest that any surface field cannot have a simple and hence easily detectable topology. Indeed, if the topology were simple the star's UV lines would be expected to show variations characteristic of a magnetic Bp star, and they do not. In recent years, the periodic magnetic signature in the star's optical light curve has disappeared (HS12), rendering a polarimetric non-detection moot at the present time.

POT17 characterize the magnetic interaction scenario for γ Cas as 'entirely phenomenological at present and lacking in predictive power'. Actually, this is not quite true. For instance, in our interaction picture hard X-ray production would cause clear changes in the attributes of the hard X-ray production, such as a disappearance of flaring, the value of $kT_{\rm hot}$, abundances determined from X-ray lines, and the Fe K fluorescence feature. The optical/UV migrating sub-features and UV 'dips' might disappear as well. The larger point is that the interaction picture connects the inner disc conditions explicitly with the X-ray production. Since the disc disappeared already in the early 20th century, we can look forward to it to disappear again and such tests to proceed. Otherwise, it is certainly true that continued observations have continually brought new surprises and necessitated changes to any posited model for the hard X-ray generation.

In all, we would say that the 'phenomenological' aspect of our magnetic interaction scenario is an expression of its adherence to a broad array of multiwavelength observations as well as being internally consistent. In fact, it seems as fair to characterize the POT17 evolutionary scenario as being dependent on critical assumptions about the mass-loss rate of the Be/Be-disc system (by hypothesis the 'disc wind') and the amount of mass available for accretion on to a degenerate companion. POT17 and we agree that this rate is not well known – indeed scant progress has been made on this hard to determine parameter.

We believe that the POT17 propeller scheme fails on the basis of the many considerations we have discussed.

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