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The X-ray emission of the γ Cassiopeiae stars

Myron A. Smith [a,*], R. Lopes de Oliveira [b,c], C. Motch [d]

[a] National Optical Astronomical Observatory, 950 N. Cherry Ave., Tucson, AZ, USA
[b] Universidade Federal de Sergipe, Departamento de Física, Av. Marechal Rondon, S/N, 49000-000 São Cristóvão, SE, Brazil
[c] Observatório Nacional, Rua Gal. José Cristino 77, 20921-400 Rio de Janeiro, RJ, Brazil
[d] Observatoire Astronomique, Université de Strasbourg, CNRS UMR7550, 11 rue de l'Université, F-67000 Strasbourg, France

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Abstract

Long considered as the "odd man out" among X-ray emitting Be stars, γ Cas (B0.5e IV) is now recognized as the prototype of a class of stars that emit hard thermal X-rays. Our classification differs from the historical use of the term "γ Cas stars" defined from optical properties alone. The luminosity output of this class contributes significantly to the hard X-ray production of massive stars in the Galaxy. The γ Cas stars have light curves showing variability on a few broadly-defined timescales and spectra indicative of an optically thin plasma consisting of one or more hot thermal components. By now 9–13 Galactic ≈B0-1.5e main sequence stars are judged to be members or candidate members of the γ Cas class. Conservative criteria for this designation are for a ≈B0-1.5e III–V star to have an X-ray luminosity of 10^{32}–10^{33} ergs s^{-1}, a hot thermal spectrum containing the short wavelength Lyα Fe XXV and Fe XXVI lines and the fluorescence FeK feature all in emission. If thermality cannot be demonstrated, for example from either the presence of these Lyα lines or curvature of the hard continuum of the spectrum of an X-ray active Be star, we call them γ Cas candidates. We discuss the history of the discovery of the complicated characteristics of the variability in the optical, UV, and X-ray domains, leading to suggestions for the physical cause of the production of hard X-rays. These include scenarios in which matter from the Be star accretes onto a degenerate secondary star and interactions between magnetic fields on the Be star and its decretion disk. The greatest aid to the choice of the causal mechanism is the temporal correlations of X-ray light curves and spectra with diagnostics in the optical and UV wavebands. We show why the magnetic star-disk interaction scenario is the most tenable explanation for the creation of hard X-rays on these stars.

Keywords: Stars: individual; Stars: massive; Stars: emission-line Be; Stars: X-ray

1. Introduction: description of γ Cas as an X-ray emitter

1.1. Early X-ray discoveries

Discovered as the first star to show Balmer line emission in its spectrum (Secchi, 1866), γ Cas has long been held out as the prototype for what became known by the mid-20th century as a large class of "classical Be" variables.[1] However, with the discovery of anomalously high X-ray flux from the direction of this star (Jernigan, 1976; Mason et al., 1976), it eventually was revealed that it is not a typical Be star after all – Be stars at large emit at most a few times more soft X-ray flux than normal B stars (Cohen, 2000), ostensibly due to shock interactions in their intermediate latitude hot winds. As we will see, the study of the generation of hard X-rays from a class of so-called "γ

* Corresponding author.
E-mail addresses: masmith@noao.edu (M.A. Smith), rlopes@ufs.br/ (R. Lopes de Oliveira), christian.motch@unistra.fr (C. Motch).

[1] Classical Be stars are main sequence or giant B stars whose spectra have shown Balmer line emission and have shown no evidence of either recent binary interactions or star formation. These stars occasionally expel matter to a centrifugally supported, thin disk, with a small opening angle, e.g., Cyr et al. (2015). The presence of disks is heralded by emission in the lower Balmer spectral lines. Our use of the term "γ Cas stars" is distinct from the definition given in the General Catalog of Variable Stars, e.g., Samus et al. (2009), and is framed within the context of X-ray characteristics, as discussed herein.

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Cas stars" links a wide field of astrophysical subdisciplines. In addition, Motch et al. (2007, "M07") and Nebot Gómez-Morán et al. (2013, "N13") have noted that γ Cas stars contribute very significantly to the X-ray flux emitted from Galactic massive stars. This makes them relevant to an understanding of the energy budget of the interstellar medium (ISM) as well as the evolutionary consequences of noncataclysmic expulsions of matter from Be binary systems.

The saga begins with the discovery that γ Cas is not just an X-ray source but a copious emitter of hard X-rays (White et al., 1982). This realization started something of a cottage industry aimed to develop an understanding of the mechanisms behind its surprising X-ray properties. The initial concept, which had been successfully applied to the generation of high energy for almost all high mass X-ray Be binary stars, is that the X-rays result from synchrotron emission (for a strongly magnetic secondary) and/or thermalization of accreted matter onto the surface, accretion column, or accretion disk hosted by a degenerate companion. In any of these scenarios the high energy emission ultimately results from the deep gravitational potential of the degenerate secondary. White et al. professed "little doubt" that γ Cas is a Be-NS (neutron star) system similar to the well known X-ray pulsar X Per. The reason for this judgment was that the light curve showed in their words a "factor of 2 quasi-periodic variations on a timescale similar to the pulsations from X Per". Here they anticipated a timescale of 13.9 min, which is the pulse period in this X-ray pulsar. In addition, White et al. rejected coronal and white dwarf (WD) accretion mechanisms. In the latter case they made this judgment because the X-ray luminosity was considered too high for WD accretion, according to the mass loss rate estimated for γ Cas. Despite these arguments it soon became clear that γ Cas is not just another example of a Be-NS system.

1.2. Recent discoveries of X-ray properties

By the end of the 20th century new generations of X-ray satellites provided data with improved spectral and time resolution. These data clarified the X-ray properties of γ Cas and a small number of "analog" members of this class and also established that the spectra were thermal and optically thin in nature. Also, the amassing of new light curves could not corroborate claims of persistent periodicities. Breakthroughs in evaluating the X-ray characteristics came from the advent of the *Rossi X-ray Timing Explorer (RXTE)* satellite, with its design purpose of providing reliable high time resolution light curves through the use of its six detectors comprising the *Proportion Counter Array (PCA)*, and from the appearance of *Chandra* and *XMM-Newton* satellites equipped with high resolution spectrometers sensitive to soft-to medium band flux (which we define somewhat arbitrarily as $\lesssim 3$ keV, i.e., $\gtrsim 4$ Ð).

The new generation light curves demonstrated that flux variability occurs on four basic timescales: rapid (seconds to a minute), intermediate (a few hours), long (a few months), and episodic (years). Meanwhile, results from turn-of-the-century X-ray spectrometers have indicated that the X-ray spectra are basically thermal. We clarify the qualifier "basically" as follows. First, one finds the continuum and the Lyman α lines of Fe XXV (1.85 Ð) and Fe XXVI (1.78 Ð) can be fit well to a primary optically thin plasma component described by a single hot energy temperature, which we will call $kT_{\rm hot}$. Second, the soft X-ray domain X-ray continuum suffers photoelectric absorption, which can be modeled by the equivalent of a hydrogen column density (hereafter $N_{\rm H}$), which is mainly attributable to the ISM as well as a local one $N_{\rm H_b}$ along the sight line to the hot plasma component. In addition, a number of emission lines in the soft X-ray waveband indicate the presence of additional cooler optically thin plasma components. If the spectral coverage is limited only to the hard X-ray region the continuum alone, one can determine a reasonably accurate value of $kT_{\rm hot}$ – but not necessarily also model the absorption column density. This is particularly true if one does not anticipate the possibility of multiple absorption columns. In such cases both the determination of $kT_{\rm hot}$ and the description of the column absorptions can be badly compromised (Smith et al., 2004, "S04").

Given these properties, γ Cas has become a compelling mystery object with more than enough surprises to attract considerable interest within the stellar X-ray community (Güdel and Nazé, 2009). In the intervening time only some of the answers we now have as to how and where the hard X-rays are created can be attributed to the latest generation of X-ray satellites. Rather, crucial new information has come with temporal correlations of contemporaneous X-ray, optical, and UV data.

1.3. General properties

1.3.1. Stellar properties

Apart from its X-ray emission, γ Cas appears to be a typical B0.5 IVe star. Its luminosity class IV is consistent with its being a field main sequence B star and having an age of $\geqslant$15—20 Myr. Herein we will assume that γ Cas has a mass near $15 M_\odot$, a revised Hipparcos distance of 168 pc (van Leeuwen, 2007), a radius of $10 R_\odot$, and an effective temperature $T_{\rm eff} = 28$ kK. With these parameters the uniform stellar disk diameter on the sky corresponds to 0.44 milliarcseconds (Stee et al., 2012). Robotic observations with the 16-inch "T3" Automated Photometric Telescope (APT) using the Johnson B and V filters consistently for more than 15 years indicate the presence of a robust signature with a period of 1.215811 ± 0.000030 days (Henry and Smith, 2012, "HS12"), which is interpreted as the rotational period of γ Cas. Indeed, when one combines the 1.2 day period with the obliquity of the star/disk system (about 45°) from Long Baseline Optical Interferometry or "LBOI" (Stee et al., 2012) one can reconcile the *vsini* value