MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Investigation of polarized and photometric radiation of a star γ Cassiopeiae

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Abstract. The study of Be stars, characterized by emission lines and rotational velocities close to critical, has long been of interest to astrophysicists. These stars are distinguished by the presence of an equatorial disk, the formation mechanism of which remains unknown. To date, no magnetic field has been detected in any of these stars. The nature of the formation of Be star disks and their magnetism is still not well understood, and explaining them is one of the most urgent and complex problems in modern astrophysics. The star γ Cassiopeiae (γ Cas) is a prominent representative of the small group of Be stars, which have increased X-ray luminosity, corresponding to abnormally high plasma temperatures. This study presents the results of a comprehensive study of the magnetic field of γ Cas using archival spectropolarimetric observations obtained with the Main Stellar Spectrograph (MSS) at the 6-m telescope BTA. The results of processing spectropolarimetric observations collected over several years made it possible to estimate the rms field of the star $B_{\rm rms} = 109 \pm 72$ G. The obtained data does not indicate the detection of global magnetic field. We assume that active regions associated with the star's local magnetic fields may be located on the surface of the star. Further research is needed to confirm this result.

Keywords: stars: emission-line, Be, magnetic field; individual: γ Cas

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1 Introduction

Among the stars of spectral class B, there are those with emission lines and rotation speeds close to the critical limit. These objects are known as classical Be stars. Another important feature of these stars is the presence of a circumstellar disk. The nature of its formation remains unknown to this day. It is detected by the presence of hydrogen emission lines in the spectra of Be stars, and sometimes lines from other elements as well.

Emission lines are often double-peaked, and their shape depends on the structure of the disk and the physical conditions within it. The optical and X-ray spectra, as well as the luminosity of Be stars, exhibit variability on short timescales. Additionally, the disks are unstable, as evidenced by the rapid variation of emission line profiles in the optical range, including complete disappearance.

Stars of spectral class B have been found to possess strong magnetic fields in about 10% of cases. However, despite extensive spectropolarimetric studies of Be stars, none have been found to exhibit a magnetic field. Notably, Hubrig et al. (2017) results indicate that a magnetic field was measured at the level of 3–4σ for the star λ Eri, but this result requires independent confirmation. The search for magnetic field in Be stars is important, because many disk formation models require the presence of a magnetic field in Be stars (for example, Brown et al. 2008).

2 General information about the star

Among Be stars, a distinct group known as γ Cas analogs can be identified, which exhibit the most pronounced unusual properties of Be stars compared to B stars. Additionally, these stars display X-ray luminosity that is 1 to 2 orders of magnitude higher than that of classical Be stars, and the temperature of the plasma emitting in the X-ray range is anomalously high ($kT \sim$ 5–30 keV).

The history of γ Cas-type stars dates back to 1866, when the spectrum of the star γ Cas itself was studied by Secchi (1866). This was the first star in which emission lines were discovered. In 1976, X-ray emission in the 2–11 keV range was detected from the SAS-3 X-ray satellite (Jernigan 1976; Bradt et al. 1977).

Güdel & Nazé (2009) presented the main characteristics of the spectrum of γ Cas. This star is a brighter X-ray source than typical Be stars, yet it is 1.5 orders of magnitude weaker than massive X-ray binaries with Be components. The X-ray spectrum itself exhibits a thermal nature characteristic of hot multicomponent plasma, with temperatures reaching up to 12 keV.

The parameters of the components of the γ Cas system, according to the literature and obtained in the present work, are presented in Table 1.

The luminosity L is estimated from its U, B, and V magnitudes using the relations provided by Nieva (2013). The correction factor A_V for interstellar extinction in the V filter is calculated using the dustmap library (Green 2018). The radius of the star is estimated using the Stefan–Boltzmann formula, employing the determined values of L and T_{eff}. The mass and age of the star have been assessed based on evolutionary tracks and isochrones, respectively, constructed using the `PARSEC` code (Bagnulo et al. 2002).

Table 1. Parameters of γ Cas A.

Parameter	Value	Reference
Spectral type	B0.5 IVe	Borre et al. (2020)
m_V, mag	2.39	SIMBAD
T_{eff}, kK	28	Smith et al. (2016b)
R, $R_\odot$	5.2	Present work
$\log g$	3.32	Chauville et al. (2001)
$\log L/L_\odot$	4.18	Present work
M, $M_\odot$	13	Smith (2019)
d, pc	117	Megier et al. (2009)
Age τ, Myr	1.6	Present work

From a statistical perspective, only 1% of Be stars exhibit properties similar to those of γ Cas. Currently, a total of 25 γ Cas-type stars and two candidates are known (Smith et al. 2016a; Nazé & Motch 2018; Nazé et al. 2020, 2022).

The criteria for identifying γ Cas-type stars are formulated by Nazé & Motch (2018). This group is characterized by high X-ray luminosity $\log L_X(0.5\text{–}10\,\text{keV}) =$ 31.6–33.2, and their spectra are defined by hardness ratios $HR \gtrsim 1.6$, where HR is the ratio of fluxes in the hard (2–10 keV) and soft (0.5–2 keV) X-ray bands. Such hardness corresponds to anomalously high plasma temperatures.

3 Observations

This study investigates the magnetism of the star γ Cas. The analysis is based on archival spectropolarimetric observations obtained at the Main Stellar Spectrograph (MSS). A total of 144 spectra in the wavelength range of 4400–4900 Å are utilized: 73 spectra were acquired on November 4, 2020, 69 spectra were obtained on January 2–3, 2021, and two spectra were collected on May 30, 2021.

4 Magnetic field measurements of γ Cas

To estimate the stellar magnetic field we used the archival spectropolarimetric observations, and employed three methods: Least Squares Deconvolution (LSD) (Donati et al. 1997), the modified differential method (MDM) (Kholtygin 2014) and the differential method (DM) (Bagnulo et al. 2002).

In the LSD method, a single mask is employed that includes 20 spectral lines. The mask is constructed based on the atomic database VALD3, with the latest implementation described by Pakhomov et al. (2017). For the modified differential method (MDM), a mask containing 12 lines was used. In this case, unblended lines with symmetric profiles were selected.

Figures 1, 2 present the results of the magnetic field measurements of γ Cas using the LSD method for November 4, 2020, and January 2–3, 2021, as a function of time.

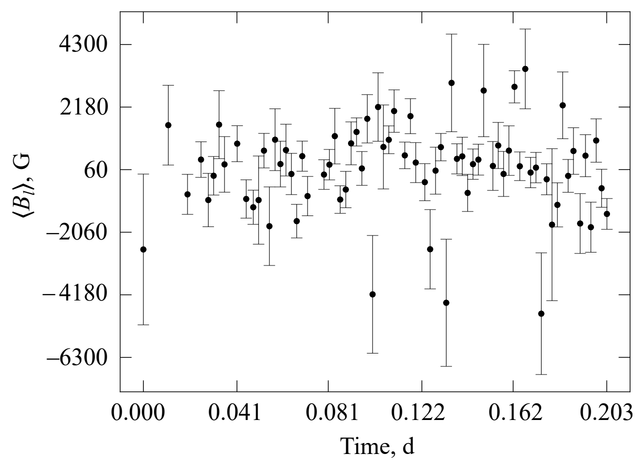

Fig. 1. The measured values of B_l, the longitudinal component of the magnetic field γ Cas, obtained from the analysis of LSD profiles as a function of time (in fractions of a day) from the beginning of observations on different days. The figure displays the measured values for November 4, 2020.

For all measured values of B_l obtained using different methods, the root-mean-square magnetic field $B_{\rm rms}$ is calculated using eq. (1).

$$B_{\rm rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\langle B_l^i \rangle)^2}. \quad (1)$$

As a result, the magnetic field $B_{\rm rms}$ values were obtained by three measurement methods. The application of the modified differential (MDM) and differential (DM) methods yields slightly different results from LSD method:

LSD: $B_{\rm rms} = 1384 \pm 809$ G; MDM: $B_{\rm rms} = 900 \pm 425$ G; DM: $B_{\rm rms} = 109 \pm 72$ G.

It is evident that the magnetic field exhibits only minor deviations from the mean value on different dates. However, the measurement of the magnetic field using three

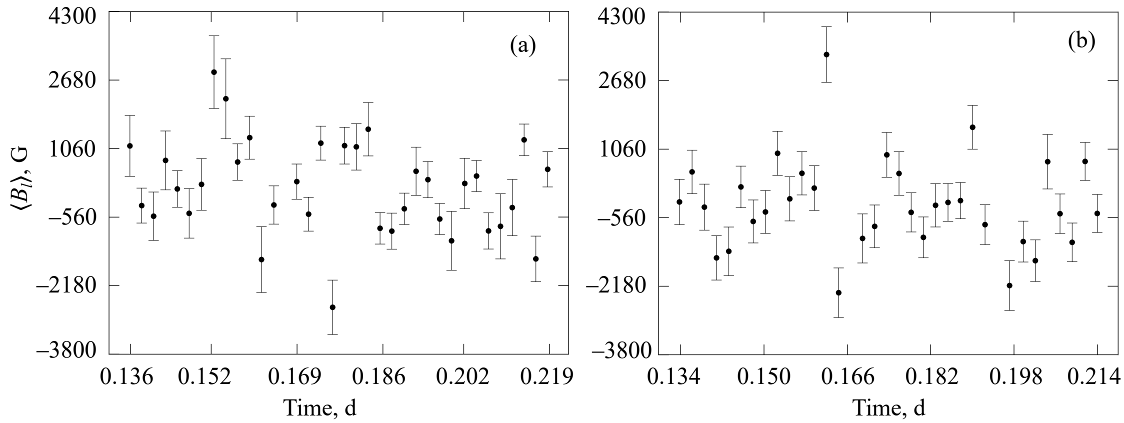

Fig. 2. The measured values of B_l, the longitudinal component of the magnetic field γ Cas, obtained from the analysis of LSD profiles as a function of time (in fractions of a day) from the beginning of observations on different days. Panel (a) for January 2, 2021, and panel (b) for January 3, 2021.

distinct methods yielded varying results. Due to the magnitude of the errors, these field values represent only upper limits for the magnetic field. Furthermore, there is no evidence to suggest that the obtained field values are associated with a global magnetic field of γ Cas.

5 Summary

As a result of the analysis of spectropolarimetric observations of γ Cas, based on 144 archival spectra using three different methods, three distinct estimates of the magnetic field were obtained. The most precise value obtained is $B_{\rm rms} = 109 \pm 72$ G, which can be considered an upper limit for the global magnetic field. Consequently, an upper limit for the magnetic field at the poles of the star can be inferred as $B_p \approx 550$ G.

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