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Stringent limits on ^{28}SiO maser emission from the recurrent nova T Coronae Borealis

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ABSTRACT
There are indications that the third known eruption of the recurrent nova T CrB is imminent, and multi-wavelength observations prior to the eruption are important to characterise the system before it erupts. T CrB is known to display the SiO fundamental vibrational feature at 8 μm. When the anticipated eruption occurs, it is possible that the shock produced when the ejected material runs into the wind of the red giant in the system may be traced using SiO maser emission. We have used the 100 m Effelsberg Radio Telescope to search for ^{28}SiO emission in the $v = 1$, $v = 2$, $J = 1 \rightarrow 0$ transitions, at 43.122 GHz and 42.820 GHz respectively, while the system is in quiescence. We find no evidence for such emission. We set stringent 3σ upper limits of 1.66 mJy on emission in the $v = 1, J = 1 \rightarrow 0$ transition, and 1.72 mJy in the $v = 2, J = 1 \rightarrow 0$ transition, respectively, for a noise bandwith of 250 kHz. The corresponding limits for a 31.25 kHz bandwidth are 4.69 mJy and 4.86 mJy respectively. These upper limits improve on previous upper limits for this system by more than two orders of magnitude.

Key words: circumstellar matter — stars: individual (T CrB) — novae, cataclysmic variables

1 INTRODUCTION

Nova eruptions arise on the surfaces of white dwarfs (WDs) in semi-detached binary systems. The secondary star in novae, usually a late-type evolved star or main sequence dwarf, fills its Roche lobe and material from the secondary forms an accretion disc around the WD. Eventually the base of the accreted envelope becomes degenerate and a Thermonuclear Runaway (TNR) ensues, resulting in a nova explosion (Bode & Evans 2012). Up to $10^{-4}\,\mathrm{M}_{\odot}$ of material, enriched in C, N, O…Ca as a result of the TNR and the ingestion of WD material into the burning region, is ejected explosively at several 100s to 1000s of $\mathrm{km\,s^{-1}}$. Eventually mass-transfer from the secondary onto the WD resumes and, in time, another nova explosion occurs. All novae are "recurrent" but in some cases the eruptions in a given system recur on a *human* ($\lesssim 100$ yrs) timescale; these are the "recurrent novae" (RNe).

Few RNe are known (see Anupama (2008) for a list), but they can be sub-divided into those with short ($\lesssim$ a day) and those with long (~ 1 yr) orbital periods. The latter generally have red giant (RG) secondaries, with the winds normally associated with RGs. RNe with RG secondaries are referred to as "symbiotic novae". When the RN in a system with a RG secondary erupts, the ejected material runs into, and shocks, the RG wind, and a shock is driven into the ejecta. This results in strong X-ray emission, and coronal line emission in the UV, optical and infrared (IR) (see, e.g., Evans et al. 2007a,b,c; Banerjee et al. 2010, 2014; Das, Banerjee &Ashok 2006; Munari et al. 2007), although photoionisation is also likely to play a part in the production of coronal line emission (Munari & Valisa 2022).

The propagation of the shock in the case of a RN eruption in a symbiotic nova system may provide a template for understanding the propagation of the shock as *supernova*

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(SN) ejecta run into the ambient medium, a process that takes centuries as opposed to days–weeks for a RN: RNe provide the opportunity to study SNe in "fast-forward", but with the additional twist of a likely density enhancement in the RN equatorial plane that may impart a bipolar morphology to the ejecta,

A key property of RNe is that the WD components have masses that are close to the Chandrasekhar Limit (Anupama 2008). The net accretion of material (i.e. accreted from the RG minus that ejected in the RN explosion) onto the WD, if positive, may in time cause it to tip over the Chandrasekhar Limit and explode as a Type Ia SN. In furthering our understanding of RNe we may therefore get a better understanding of Type Ia s, which are of course key in the determination of cosmic large-scale structure (Perlmutter et al. 1997; Reiss et al. 1998). The study of RN eruptions therefore has applications well beyond the confines of cataclysmic variable systems.

2 THE RN T CrB

T CrB is a RN with a RG secondary (Anupama 2008); it last erupted in 1946; its orbital period is 227.67 d (see, e.g., Anupama 2008). The recent rise in the optical flux (Munari, Dallaporta & Cherini 2016), with concurrent changes in the X-ray flux (Luna et al. 2018) point to the likelihood that its next eruption is imminent (Schaefer 2010; Munari et al. 2016). Luna et al. (2018) attributed the increased activity to changes in the boundary layer; such an increase might arise from a surge in the mass-transfer rate from the RG to the WD. While the cause of such a surge is unclear, a consequence is that the amount of material in the environment of the RG has been substantially enhanced. More recently, Luna et al. (2020) have drawn attention to a striking resemblance between the pre-1946 eruption B-band light curve and the current (2022) B light curve. They suggest that the WD in T CrB is currently undergoing a high rate of accretion, possibly due to accretion disc instabilities that are commonly seen in dwarf novae. They predict that the next RN eruption in T CrB is likely to occur within the next 6 years.

The circumstellar envelopes (CSE) around evolved O-rich stars such as Mira variables and other Asymptotic Giant Branch (AGB) stars provide suitable conditions for maser emission (see, e.g., Gray 2012), and these are found even in the presence of symbiotic interaction with a companion. In 2009, Cho & Kim (2010) used the Yonsei 21-m telescope to survey 47 symbiotic stars, with on-source integration times in the range 30–50 miutes. They detected 43 GHz SiO maser emission from nineteen of these, and 22 GHz H_2O maser emission from nine (seven of which also have SiO masers). The higher SiO maser detection rate is likely to be because the conditions for SiO masing occur closer to the star where the CSE is less likely to be disrupted by the companion (see, e.g., Gray 2012; Richards et al. 2020). Cho & Kim (2010) did not detect T CrB, with 3σ upper limits on the peak antenna temperatures of 60 mK in the ^{28}SiO and ^{29}SiO isotopologues, corresponding to 3σ upper limits on the flux density of 0.69 Jy over a bandwidth of 31.25 kHz.

The observations by Cho & Kim (2010) were made on 2009 November 5, when the RG component was eclipsing the WD, so irradiation effects were unimportant. The signifcance of this for the case of T CrB is that the RG component of the symbiotic nova V407 Cyg displays SiO maser emission. When V407 Cyg erupted in 2010, material ejected in the nova explosion disrupted the maser-bearing region around the RG, but it was re-established after a couple of weeks (Deguchi et al 2011). An alternative interpretation is that the initial flash-ionisation extended to the maser region, and destroyed the conditions for masing; the outer wind then recombined in $\sim$ two weeks, and maser emission resumed. The inner wind of the RG in V407 Cyg recombined on an e-folding time of 4.0 days (Munari et al. 2011), and a longer interval is to be expected in the lower density external regions from where maser emission originates. Whatever the cause of the destruction and re-establishment of the maser region, it was possible to use the maser to trace the progress of the shock through the atmosphere of the Mira component (Deguchi et al 2011).

The prospect of replicating the Deguchi et al (2011) observations when T CrB next erupts is an exciting one. Such an observation, complemented by optical and IR data, would provide unique insight into the physics of shock evolution in a stellar, and in particular a RN, environment. This possibility arises from a 2007 Spitzer Space Telescope (Werner et al. 2004; Gehrz et al. 2007) InfraRed Spectrograph (Houck et al. 2004) observation of T CrB that revealed the presence of absorption in the SiO fundamental vibrational band at 8 μm, which had contibutions from both the RG photosphere and the RG wind (Evans et al. 2019). The SiO column was determined to be 2.8×10^{17} cm^{-2}, and the temperature ~ 1000 K. It was this detection that prompted us to observe T CrB in the $\upsilon = 1, 2, J = 1 \rightarrow 0$ transitions of ^{28}SiO.

We should note, however, that a reanalysis of the Spitzer data (Evans et al. 2022) showed that the wind reported by Evans et al. (2019) was spurious. The earlier work considered only the contribution of the ^{28}SiO isotopologue: the inclusion of other SiO isotopologues accounted satisfactorily for the 8 μm absorption in terms of photospheric SiO only, without the need for a wind.

Notwithstanding this later result, we report here on an observation of T CrB in the $\upsilon = 1$, $\upsilon = 2$, $J = 1 \rightarrow 0$, transitions of ^{28}SiO.

3 OBSERVATIONS

T CrB was observed in the $\upsilon = 1$, $\upsilon = 2$, $J = 1 \rightarrow 0$, transitions at the respective frequencies of 43.122 GHz and 42.820 GHz using the 100 m Effelsberg Radio Telescope (Altenhoff et al. 1980). The observation in the Q-band employed the 7.0 mm secondary-focus receiver with the XFFS backend, with 65536 spectral channels. The total bandwidth was 500 MHz; the channel width in this configuration is 7.629 kHz (0.053 km s^{-1} at a frequency of 43 GHz). The system-equivalent flux density (SEFD) is assumed to be that measured at 44.1 GHz in 2019 December[1], i.e. 140 Jy. The line frequency was set at 42.971335 GHz, midway between the frequencies of the SiO transitions. The bandwidth was

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[1] https://eff100mwiki.mpifr-bonn.mpg.de/doku.php?id=information_for_astronomers:rx:s7mm_db

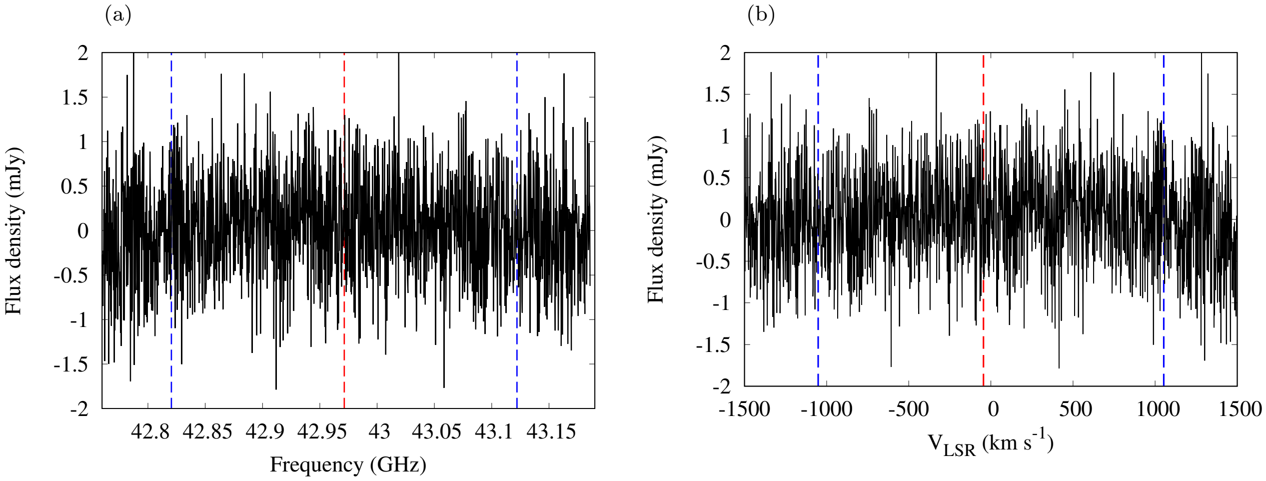

Figure 1. (a) spectrum over the observed frequency range; data have been binned in 250 kHz bins. (b) as (a), but in $V_{\rm LSR}$ frame, converted using the mean frequency of the two SiO transitions. In (b) the red vertical line denotes the $V_{\rm LSR}$ of T CrB; the two blue vertical lines denote the $V_{\rm LSR}$ at which the two SiO transitions would be observed if present. In (a), the lines correspond, in frequency space, to the lines in (b).

such that both transitions would be captured, including allowances for uncertainties in the radial velocity.

The observations were carried out on three occasions, 2021 February 4, February 12 and February 23-24; at all these times the WD component was eclipsed by the RG. This ensured that there were no complications due to irradiation of the visible RG atmosphere by hard radiation from the WD that might disrupt any SiO maser zone. However weather conditions during the two earlier runs were poor, and only the data obtained on February 23-24 are presented here. Each observation was corrected to the $V_{\rm LSR}$ appropriate at the time of observation, and the corrected observations averaged.

The heliocentric velocity of T CrB is given by Fekel et al. (2000) as $-27.79\pm0.13\,{\rm km\,s^{-1}}$; *Gaia* DR2 (Gaia Collaboration 2016, 2018) gives $-27.1\pm6.9\,{\rm km\,s^{-1}}$. We use the Fekel et al. value here, to give $V_{\rm LSR}=-44.8\,{\rm km\,s^{-1}}$ for T CrB. Allowance has to be made for the orbital motion of T CrB, although as it was observed in the above window this would have been minimal. However, the wind velocity ($-19\,{\rm km\,s^{-1}}$ for T CrB; Munari et al. 2016) — which will be at maximum as the RG passes at inferior conjunction — might also have an effect on the observed frequencies of the transitions.

T CrB was observed for a total of 8 hours on February 23-24. The same time was taken for calibration via position switching, and the observations of standard flux calibrators. For the flux density calibration the spectra were corrected for the atmospheric absorption and the gain-elevation effect (loss of sensitivity due to the gravitational deformation of the main dish). The conversion factor from antenna temperature to flux density in Jy was determined by regular observations of 3C 286. Calibration uncertainties are estimated to be $\sim 10\%$. We note that the observing time was negligible by comparison with the orbital period; therefore the orbital motion had no impact on the observation. The GILDAS/CLASS2 packages (Pety 2005) were used in the spectral line data reduction.

4 RESULTS

The width of the ^{28}SiO $\upsilon=1, J=1\rightarrow0$ transition, as measured by a single aperture, in the oxygen-rich AGB star R Cas is $\sim 1-2\,{\rm km\,s^{-1}}$ (Assaf et al. 2011), corresponding to a bandwidth of 250 kHz. Our spectrum of T CrB was therefore binned into 250 kHz bins; the averaged spectrum is shown in Fig. 1(a), Fig. 1(b) shows the spectrum in terms of $V_{\rm LSR}$. Clearly there is no obvious emission corresponding to the two SiO transitions considered here.

In order to place upper limits on the ^{28}SiO emission, we consider two noise bandwidths. First, we use 250 kHz, as in Fig. 1, corresponding to the typical width of an SiO maser line. The 3σ upper limits in this case are 1.66 mJy for the $\upsilon=1, J=1\rightarrow0$ transition, and 1.72 mJy in the $\upsilon=2, J=1\rightarrow0$ transition. For a more direct comparison with the work of Cho & Kim (2010), who used a 64 MHz bandwidth with 2048 channels for their SiO observations, we use a bandwidth of 31.25 kHz. Over this bandwidth our 3σ upper limits are 4.69 mJy ($\upsilon=1$) and 4.86 mJy ($\upsilon=2$). Given the larger aperture and the much longer integration times in our study, it is not surprising that our limits improve on those reported by Cho & Kim (2010) by more than two orders of magnitude.

5 CONCLUSIONS

We have searched for 42.820 GHz and 43.122 GHz maser emission from ^{28}SiO in the circumstellar environment of T CrB. We find no evidence for such emission.

Nonetheless we strongly encourage a repeat of these observations when T CrB does eventually erupt. The prospect of tracing the shock through the wind of the RG component, which may be confined to a ring inclined to the orbital plane (Theuns & Jorissen 1993; Booth, Mohamed & Podsiadlowski 2016), is one that will surely be too good to miss. Monitoring of T CrB at these frequencies is ongoing.

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DATA AVAILABILITY

The data underlying this paper will be shared on a reasonable request to the corresponding author.

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