CONSTRaining THE X-RAY LUMINOSITIES OF ASYMPTOTIC GIANT BRANCH STARS:
TX CAMELOPARDALIS AND T CASSIOPEIA

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ABSTRACT

To probe the magnetic activity levels of asymptotic giant branch (AGB) stars, we used XMM-Newton to search for X-ray emission from two well-studied objects, TX Cam and T Cas. The former star displays polarized maser emission, indicating magnetic field strengths of $B \approx 5$ G, and the latter is one of the nearest known AGB stars. Neither star was detected by XMM-Newton. We use the upper limits on EPIC (CCD detector) count rates to constrain the X-ray luminosities of these stars and derive $L_X \lhd 10^{31}$ erg s$^{-1}$ ($\lhd 10^{30}$ ergs s$^{-1}$) for an assumed X-ray emission temperature $T_X = 3 \times 10^6$ K ($10^7$ K). These limits represent $\approx 10\%$ ($\leq 1\%$) of the X-ray luminosity expected under models in which AGB magnetic fields are global and potentially play an important role in collimating and/or launching AGB winds. We suggest, instead, that the $B$ field strengths inferred from maser observations are representative of localized magnetic clouds.

Subject headings: stars: AGB and post-AGB — stars: magnetic fields — stars: mass loss — stars: winds, outflows — X-rays: ISM

1. INTRODUCTION

There has been considerable recent debate over the potential role of magnetic fields in launching and/or shaping winds from asymptotic giant branch (AGB) stars (Soker & Kastner 2003 and references therein). Of special interest are detections of maser polarization around some AGB stars, which indicate the presence of relatively strong magnetic fields (e.g., Zijlstra et al. 1989; Kembell & Diamond 1997; Miranda et al. 2001; Vlemmings et al. 2002; Bains 2004). SiO maser polarization measurements are particularly important in this regard, as these observations probe the important transition region between the AGB stellar photosphere and the wind. Based on high-resolution polarization maps of SiO masers, Kembell & Diamond (1997) deduce a magnetic field of $B \approx 5 - 10$ G at a radius of $\approx 3.5R_*$ around the AGB star TX Cam, a Mira variable. Here $R_*$ is the stellar radius, which we take to be $\approx 2$ AU (see discussion in Kembell & Diamond 1997). With a dependence on radius of $B \propto r^{-2}$ (Vlemmings et al. 2002), this suggests a stellar-surface magnetic field of $B_* \approx 50 - 100$ G. Miranda et al. (2001) find polarization in the 1665 MHz OH maser line, which indicates the presence of $\approx 10^{-5}$ G magnetic fields at $\sim 10^{-4}$ cm from the central star of the young planetary nebula (PN) K 3-35.

Miranda et al. (2001) claim that their results favor magnetic collimation models of outflows in PNs. The results for TX Cam, which will presumably undergo a PN phase, could be similarly interpreted to suggest that such magnetic collimation begins well before ionization of the circumstellar envelope. Indeed, in summarizing water maser polarization measurements for several giants, Vlemmings et al. (2002) conclude that magnetic fields are strong enough to drive and shape winds from AGB stars.

However, these observations of polarized maser emission also could indicate the presence of localized, highly magnetized wind clumps, analogous to magnetic clouds in the solar wind (Soker & Kastner 2003), rather than large-magnitude global magnetic-field strength (Soker 2002, 2003; Soker & Kastner 2003; Soker & Zoabi 2002). In that respect, we note the recent results of Murakawa et al. (2003), who find that the H$_2$O maser clouds around the red supergiant VX Sgr are $\approx 300$ times denser than the surrounding wind. On the theoretical side, based on a dynamo model for the cool supergiant Betelgeuse, Dorch (2003) finds that the magnetic structure has a typical scale of $\approx 0.15R_*$, smaller than the giant convection cells.

Soker & Zoabi (2002) summarize possible problems in models in which the magnetic field plays a dynamical role in shaping the AGB wind. Among others, they consider the X-ray luminosity ($L_X$). They argue that, as in the Sun, globally strong magnetic fields will violently reconnect, generating flares that lead to strong X-ray emission. Such a close coupling between stellar magnetic flux and X-ray luminosity has been demonstrated to extend over $12 - 13$ orders of magnitude in $L_X$ (Pevtsov et al. 2003). Soker & Zoabi find that for $B_* \gtrsim 1$ G on AGB stars, the expected X-ray luminosity is $\gtrsim 10^4$ times stronger than that of the Sun, if the reconnection rate per unit surface area is similar. Likewise, if the X-ray luminosity is proportional to the optical luminosity, the same scaling factor (from solar to AGB X-ray luminosity) holds.

One might even expect that AGB star X-ray surface fluxes are disproportionately larger than solar. This expectation is based on the fact that for the Sun—where the mass-loss rate is governed by magnetic activity—the average X-ray luminosity is of the same order of magnitude as the rate of kinetic energy carried by the wind. The X-ray luminosity in the soft X-ray band (that of the ROSAT Position Sensitive Proportional Counter [PSPC], i.e., $0.1 - 2.4$ keV) is in the range $\sim 3 \times 10^{26}$ to $\sim 5 \times 10^{27}$ ergs s$^{-1}$ at solar minimum and maximum, respectively (Peres et al. 2000). The solar wind’s kinetic energy falls between these values. If this is the case for AGB stars, as proposed in the dynamic-magnetic models, then the X-ray luminosity should be a factor of $\approx 10^6 - 10^8$ stronger than in the Sun (Soker & Zoabi 2002). Soker & Zoabi (2002) conclude that this expectation, of $L_X \sim 10^{31} - 10^{33}$ ergs s$^{-1}$, is in sharp contradiction with most ROSAT observations; these
observations demonstrate that the X-ray luminosities of red giant stars typically are only marginally larger than the solar X-ray luminosity (Schröder et al. 1998) and that \( L_X \) likely further decreases in late giant evolution (Hünsch & Schröder 1996). On the other hand, some red giants are known to be relatively luminous in X-rays (i.e., \( L_X \sim 10^{30} \) erg s\(^{-1}\); e.g., Hünsch & Schröder 1996; Hünsch 2001).

In Soker & Kastner (2003), we discuss flares on AGB stars from locally, rather than globally strong fields. Such fields should result in much weaker X-ray emission (Soker & Zaqabi 2002; Pevtsnov et al. 2003). It is possible that such weak coronal X-ray emission from heavily obscured, mass-losing AGB stars has escaped detection thus far, due to ROSAT’s lack of hard X-ray sensitivity and the large distances to these short-lived, luminous stars. Indeed, Mira itself is a weak \( ROSAT \) X-ray source (\( L_X \sim 2 \times 10^{30} \) ergs s\(^{-1}\); Karovska et al. 1996; Soker & Kastner 2003), although the origin of its X-ray emission is uncertain, given the presence of a close companion.

In an attempt to further constrain models for magnetic fields in AGB stars, we are conducting observations of selected AGB stars with the \( XMM-Newton \) X-ray observatory, which features sensitivity and energy coverage far superior to that of \( ROSAT \). In this paper we report on and discuss results from \( XMM-Newton \) observations of the polarized maser source TX Cam and the nearby AGB star T Cas. Like TX Cam, T Cas is a relatively strong SiO maser source (Herpin et al. 1998), although we are unaware of measurements of the polarization of its maser emission or high-resolution imaging of its maser spots.

2. OBSERVATIONS AND RESULTS

We observed the TX Cam and T Cas fields with \( XMM-Newton \) on 2003 September 4 and February 6, respectively. The observatory’s three co-aligned telescopes provide imaging in the 0.1–15 keV energy range, with a field of view of \( \sim 25'\) and a 50% encircled energy diameter of 15'. The instrument of interest for these observations was EPIC, with its three photon-counting CCD detector systems (pn, MOS 1, and MOS 2). The spectral resolution of these CCD systems ranges from \( \sim 50 \) to \( \sim 150 \) eV over the energy range of interest (0.1–10 keV). The thick filter was used for all three detectors to suppress detection of visible-light photons from these optically bright targets. Total EPIC integration times, broken down by detector, are listed in Table 1.

The 0.2–10 keV background count rate for each observation with a given detector (pn, MOS 1, or MOS 2) was obtained from the total number of counts within an annulus centered on the stellar position, where the annulus extends from 35' to 70' in radius. These measured background count rates (Table 1) are consistent with those expected from the internal “quiescent” EPIC background combined with small contributions from external background sources (see the \( XMM-Newton \) Users’ Handbook).\(^3\)

The count rates within 18' radius, circular source-extraction regions centered on the stellar positions were found to be consistent with the surrounding background rates. We conclude that no X-ray sources were detected above background at the optical positions of TX Cam and T Cas in these observations. We then obtain 3 \( \sigma \) upper limits on the 0.2–10 keV count rate for each source from the count-rate variances within the source-extraction regions, based on Poisson counting statistics (Table 1).

While no X-ray source was detected at the position of either AGB star, these observations did yield the first-time detection of \( \sim 12 \) and \( \sim 40 \) X-ray sources in the TX Cam and T Cas fields, respectively. The identification of these sources, most of which have no cataloged optical or infrared counterparts, will be the subject of a future paper.

2.1. Upper Limits on \( L_X \) for TX Cam and T Cas

To derive upper limits on \( L_X \) from the EPIC count rate upper limits in Table 1, we used the XSPEC\(^4\) software to compute intrinsic (unabsorbed) source fluxes for a grid of representative \( T_X, N_H \) values. We assumed a standard Raymond-Smith plasma-emission model (Raymond & Smith 1977) with intervening absorption defined by the XSPEC \( wabs \) function (Morrison & McCammon 1983) and used EPIC spectral response matrices calculated for the specific source-extraction regions.

The models were constrained to reproduce the observed merged MOS 1 and MOS 2 upper limit of 2.5 ks\(^{-1}\) for TX Cam; the pn count rate upper limit is less useful because of the limited exposure time for the TX Cam observation. Resulting

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\(^3\) For detailed information concerning \( XMM-Newton \) and its instrumentation, see http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/index.shtml.

\(^4\) See http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/.
upper limits on intrinsic source X-ray flux, $F_X$, are displayed in Figure 1. To calculate upper limits for $L_X$ from $F_X$, we take the distance to TX Cam to be 320 pc (Patel et al. 1992). The limiting values for $F_X$ and $L_X$ in Figure 1 are based on 3 $\sigma$ upper limits on the count rate and therefore would become somewhat more stringent if we relax the nondetection threshold.

For T Cas, the EPIC upper limits are marginally smaller because of the additional pn integration time, and Figure 1 can be taken to represent somewhat more conservative upper limits on $F_X$ from our *XMM-Newton* data for this star. Note that T Cas may be only half as distant as TX Cam (previous estimates range from 160 to 280 pc; Loup et al. 1993), in which case the upper limits on $L_X$ implied by our nondetection would be considerably more stringent than the results for TX Cam in Figure 1.

3. DISCUSSION

3.1. Predicted X-Ray Luminosity of TX Cam

The X-ray luminosity due to magnetic activity associated with an AGB star can be predicted in a variety of ways, by analogy with the Sun. First, we can predict $L_X$ from the kinetic energy carried by the wind of the star, $E_w$, assuming the magnetic field is dynamically important (Soker & Zoabi 2002); in the case of the Sun, $L_X \approx E_w$. The wind speed of TX Cam is $v_w \approx 10$ km s$^{-1}$, and its mass-loss rate is $\dot{M} \approx 10^{-6} M_6$ yr$^{-1}$ (where the former quantity is obtained directly from its spherically symmetric mass loss at a constant rate. In fact, the magnetic field is global and carried by the AGB wind.

For T Cas, we can also predict $L_X$ from the rate of magnetic energy carried by the wind, $E_B \approx 4\pi v^2 \approx B^2 / 8\pi$, by applying a scale factor between $E_B$ and $L_X$ that is obtained from the Sun. For the canonical solar surface magnetic field value of $B \approx 1$ G and wind speed of $v \approx 500$ km s$^{-1}$, we find $E_B \approx 10^{29}$ ergs s$^{-1}$, which is 100 times the X-ray luminosity of the Sun. From the magnetic field strength inferred from maser polarization measurements of TX Cam, $B \approx 5$ G at $r \approx 7 \times 10^{13}$ cm (Kemball & Diamond 1997), we find $E_B \approx 6 \times 10^{30}$ ergs s$^{-1}$, if this field is carried outward at $v \approx 10$ km s$^{-1}$ (this is an oversimplification, as the kinematics of the maser spots is quite complicated; Diamond & Kemball 2001, 2003).

Applying the solar scale factor between the rate of magnetic energy loss and $L_X$ to TX Cam, we then predict $L_X \approx 5 \times 10^{32}$ ergs s$^{-1}$, under the assumptions that the TX Cam magnetic field is global and carried by the AGB wind.

Both of these estimates, in turn, are similar to what one would predict based on the relationship between average (global) solar magnetic flux and solar $L_X$ (Pevtsov et al. 2003) and then scaling $L_X$ up according to the magnetic flux of TX Cam, assuming a global magnetic field of $B \approx 5$ G at $r \approx 1000 R_\odot$.

We therefore estimate that the expected X-ray luminosity of TX Cam is in the range $L_X \sim 3 \times 10^{31} - 5 \times 10^{32}$ ergs s$^{-1}$, for a globally and/or dynamically important stellar magnetic field that is of the magnitude measured from SiO maser polarization. Similar arguments should pertain to T Cas, although estimates of $B$ are unavailable for this star because of the lack of SiO polarization measurements.

3.2. X-Ray Absorption by AGB Winds

Given its mass-loss rate of $M \approx 1.1 \times 10^{-6} M_6$ yr$^{-1}$ (Knapp & Morris 1985), the wind of TX Cam could have a large column density. Integrating along the line of sight down to a radius of $R_X$ and assuming the wind is expanding with constant speed of $v_w \approx 10$ km s$^{-1}$ and mass-loss rate of $M \approx 10^{-6} M_6$ yr$^{-1}$, the total (ionized and neutral) H column density would be

$$N_H, \text{ wind} \approx 10^{23} \left( \frac{v_w}{10 \text{ km s}^{-1}} \right)^{-1} \left( \frac{M}{10^{-6} M_6 \text{ yr}^{-1}} \right) \times \left( \frac{R_X}{2 \text{ AU}} \right)^{-1} \text{ cm}^{-2}. \quad (1)$$

Here $R_X$ is the radius where the X-ray emission by magnetic activity takes place. For such a large column density, the optical depth is $\tau \approx 100$ at 0.5 keV (50 at 1 keV), assuming a wind opacity similar to that of the interstellar medium (ISM; see Draine & Tan 2003). The mass-loss rate of T Cas is $\sim 3 \times 10^{-7} M_6$ yr$^{-1}$, and its wind speed is $v_w \approx 6$ km s$^{-1}$ (Loup et al. 1993), yielding a similar estimate for $N_H$ from equation (1) (assuming an $R_X$ similar to that of TX Cam).

If equation (1) holds, we would not obtain meaningful upper limits on $L_X$ from our nondetections of TX Cam and T Cas with *XMM-Newton* (Fig. 1). There is reason to suspect, however, that equation (1) substantially overestimates $N_H$. If $N_H \approx 10^{23}$ cm$^{-2}$ and the ISM relationship between $N_H$ and $A_V$ (e.g., Draine & Tan 2003) applies here, equation (1) would suggest $A_V \approx 60$. Yet both stars are moderately bright in the visual. For TX Cam (spectral type M8.5), $V$ varies between $\sim 16.2$ and $\sim 11.6$ (with a 557 day period; Kukarkin et al. 1971). We then obtain a firm upper limit of $A_V < 9$ by noting that $V - K < 16$ for TX Cam, whereas $V - K > 7$ for very late-type M giants (Johnson 1966). Applying the same method to T Cas (M7e), which displays $V$ of between $\sim 12.4$ and $\sim 7.3$ (Kukarkin et al. 1971) and $V - K < 13$, we find $A_V < 6$. We conclude that $N_H < 10^{22}$ cm$^{-2}$ for both stars, with $N_H$ toward T Cas somewhat smaller than toward TX Cam.

The discrepancy between this optically derived upper limit for $N_H$ and the estimate obtained via equation (1) likely reflects the fact that equation (1) relies on the assumption of spherically symmetric mass loss at a constant rate. In fact, the...
combination of relatively bright CO radio line emission and moderate $A_V$ suggests that either (1) these stars are losing mass primarily along their equatorial planes and are observed toward relatively high latitudes along our line of sight or (2) the relatively intense mass loss that resulted in their expanding molecular envelopes occurred in short-lived episodes (as has been observed in the case of many other AGB stars).

Furthermore, there is reason to expect that $N_{\text{H}}$ may be somewhat smaller than either of the above estimates suggest. If magnetic fields indeed shape the wind, we expect that some X-radiation will escape along directions of lower density and/or lower opacity. Several different models for nonspherical mass loss invoke magnetic fields (e.g., Pascoli 1997; Matt et al. 2000; García-Segura & López 2000; Blackman et al. 2001), such that we might expect enhanced magnetic activity in regions of lower density. In addition, the hot coronal gas formed by the magnetic activity above active regions could have much reduced opacity because many species will be highly ionized, thus reducing the photoelectric absorption. Finally, if the dust-to-gas ratios in the TX Cam and T Cas envelopes are significantly larger than the “canonical” ISM value of $\sim 0.01$, the effective loss of metals from the gas phase likely would further reduce $N_{\text{H}}$ (Wilms et al. 2000).

3.3. What is $T_X$ for TX Cam (and T Cas)?

If $N_{\text{H}} \gtrsim 10^{22}$ cm$^{-2}$ and AGB magnetic reconnection events yield circumstellar plasma conditions similar to those of the solar corona ($T_H \sim 2 \times 10^6$ K; e.g., Pevtsov et al. 2003), then much of the resulting (soft) X-ray emission could be attenuated by the AGB envelopes and our nondetections would have less significance (Fig. 1). However, while the correlation between magnetic flux and $L_X$ is quite robust (Pevtsov et al. 2003), the relationship (if any) between stellar magnetic fields and the temperature of X-ray emission has yet to be established. For stars of spectral type F and later, it appears that X-ray emission softens monotonically with stellar age from pre–main-sequence (T Tauri) through main-sequence stages (Kastner et al. 2003 and references therein). But this X-ray spectral evolution may be due to decreasing pre–main-sequence disk-accretion rates and/or circumstellar $N_{\text{H}}$ or to changing plasma abundance anomalies; in any event, there is no reason to expect that the trend should continue into post–main-sequence evolution. Indeed, AGB star magnetic activity may have more in common with T Tauri star activity than with pre–main-sequence activity, in which case we might expect relatively hard X-ray emission and intense flaring (Feigelson et al. 2002). In this regard it is intriguing that Mira displays $T_X \sim 10^7$ K (Soker & Kastner 2003), i.e., hotter than the solar corona (although this emission may originate from Mira’s nearby companion; Karovska et al. 1996).

4. CONCLUSIONS

Given the above considerations, we tentatively place upper limits of $L_X < 10^{31}$ ergs s$^{-1}$ on the X-ray luminosities of TX Cam and T Cas (Fig. 1). If the X-ray emission due to magnetic activity is relatively hard, then the upper limits become far more stringent: e.g., $L_X < 10^{30}$ ergs s$^{-1}$ for $T_X = 10^7$ K and $N_{\text{H}} < 10^{22}$ cm$^{-2}$.

In light of the large uncertainties, these results do not rule out the claim that magnetic fields shape the winds from AGB stars. However, it seems that the nondetection of TX Cam, in particular, strongly constrains such models. Given the evidence for relatively strong magnetic fields around this star and the tight coupling between stellar magnetic flux and $L_X$ (e.g., Pevtsov et al. 2003), the upper limit on TX Cam’s X-ray luminosity indicates that the magnetic field behavior is much quieter and/or that its active regions are far less widespread than on the Sun. Yet AGB stars, like TX Cam, have very strong convective envelopes, pulsate strongly, and lose mass at high rates. We expect that all these characteristics should lead to a much more chaotic magnetic field structure than on the Sun, with more violent reconnection and liberation of magnetic energy (Soker & Kastner 2003).

Our conclusion—although not firm, due largely to lingering uncertainties in $T_X$ and $N_{\text{H}}$—is that TX Cam and T Cas are not strong X-ray sources, and hence their average magnetic fields are much weaker than would be required to collimate and/or drive their AGB winds. Instead, the magnetic field must be concentrated in small regions, some of which give rise to the polarized maser emission from TX Cam (Soker & Kastner 2003). Note that some magnetic activity, accompanied by much weaker X-ray luminosity than that expected for a global magnetic field, is still expected in our local field model (Soker & Kastner 2003).

Clearly more work on both the theoretical and observational aspects of AGB star magnetic fields is needed. High-resolution polarization mapping of SiO emission from T Cas and other relatively nearby bright maser sources is called for, as are additional, sensitive X-ray observations of AGB stars with moderate $B$ fields, as inferred from maser polarization and other methods. We also suggest more attention be paid to post–main-sequence magnetic activity models in which the fields are local and have no global dynamical role.

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