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LIMITS TO MASS OUTFLOWS FROM LATE-TYPE DWARF STARS

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ABSTRACT

We show that the mass-loss rates of active late-type dwarf stars must be significantly lower than recent estimates of up to $\sim 5 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, 4 orders of magnitude higher than that of the Sun. First, we present aperture-synthesis observations at 3.5 mm of the dMe flare stars YZ CMi and AD Leo, during which neither star was detected at an upper limit of 10 mJy. Although compatible with the tentative detection of YZ CMi at 1.1 mm reported by Mullan and coworkers if the millimeter emission originates from a $\sim 10^4$ K, 300 km s^{-1} wind with $\dot{M} \approx 5 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, we show that such a wind would completely absorb the observed radiation from coronal radio flares originating from close to the stellar surface. From this contradiction, we show that the mass-loss rate of any $\sim 10^4$ K wind with solar-wind–like velocities of 300–600 km s^{-1} must be less than $\sim 10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$, more than 3 orders of magnitude below that inferred by Mullan et al. The corresponding upper limit to a wind at a solar-wind–like temperature of $\sim 10^6$ K is $\dot{M} \approx 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$, an order of magnitude below the lower limit predicted theoretically by Badalyan & Livshits. Our arguments apply to all classes of stars that display coronal radio flares, implying that the mass-loss rate of active late-type dwarf stars from any $\sim 10^4$ or $\sim 10^6$ K winds with solar-wind–like velocities can be no more than 1 or 2 orders of magnitude, respectively, higher than the solar mass-loss rate of $\sim 3 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$. We show that coronal mass ejections also are unlikely to explain the reported millimeter emission from dMe flare stars, and that the time-averaged mass-loss rate from such events can be no higher than in the case of a steady, spherically symmetric stellar wind.

Subject headings: radio continuum: stars — stars: activity — stars: coronae — stars: late-type — stars: magnetic fields — stars: mass loss

1. INTRODUCTION

The Sun experiences continuous mass loss from a wind at a mean rate of $\sim 3 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$. The solar wind, which is at coronal temperatures of $\sim 10^6$ K, can be separated into two components: a relatively fast ($\sim$600 km s^{-1}) but low-density wind that emanates from coronal holes (known as the fast wind) and a relatively slow ($\sim$300 km s^{-1}) but high-density wind that is associated with high magnetic arches (the slow wind). The fast wind is thought to account for the larger fraction of the Sun's mass loss from its wind. The Sun also experiences transient mass loss from coronal mass ejections (CMEs). The latter occur when large magnetic loop structures become unstable and accelerate outward (reaching velocities of 100–1000 km s^{-1}), carrying with them massive amounts of coronal plasma. Integrated over time, the mass loss from CMEs is about an order of magnitude less than that from the solar wind.

Our knowledge of the mass loss on other late-type dwarf stars is, by comparison, rudimentary. Observations using the Zeeman technique suggest that kilogauss magnetic fields can cover nearly the entire photosphere of highly active dMe flare stars (Saar 1987); nevertheless, there will presumably still be open field lines where a fast wind can emerge, although the area of open fields may well be smaller than on the Sun. The possibility of a stellar wind analogous to the slow solar wind has been examined by Badalyan & Livshits (1992), who predict that the stars thought to be magnetically saturated can have winds with a mass-loss rate exceeding $\sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$. Their high mass-loss rates arise from the assumption of a base density in the magnetic arches equal to that of the X-ray–emitting material in the corona, and a relatively large area for the footpoints of the arches.

Perhaps the best evidence that active late-type stars may have a strong wind comes from observations of the eclipsing binary system V471 Tau, which comprises an active K2 dwarf and a white dwarf. The ultraviolet (UV) continuum of active late-type dwarf stars is too weak to reveal line absorption by a stellar wind, but in the V471 Tau system the strong photospheric UV emission of the white dwarf can be used to illuminate the extrastellar environment of the K dwarf. In this way, Mullan et al. (1989) reported the detection of discrete UV absorption features which they attribute to a relatively cool ($\sim 10^4$ K) wind from the K dwarf with a velocity of $\sim$500 km s^{-1} and a mass-loss rate of $\sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$. The existence of such a strong wind from the K dwarf in V471 Tau, however, has been criticized by Lim, White, & Cully (1996). These authors showed that the radio emission of V471 Tau experiences periodic eclipses, which implies the existence of a nonthermal radio source located between the K dwarf and the white dwarf which is periodically blocked by the K dwarf's optical disk. The very fact that this radio source is detectable implies that any wind from the K dwarf must be optically thin, which is unlikely to be the case if it has the temperature and mass-loss rate inferred by Mullan et al. (1989).

In apparent support of such high mass-loss rates from active late-type dwarf stars, first Doyle & Mathioudakis (1991) and then Mullan et al. (1992) reported the detection of a number of dMe flare stars at 0.8, 1.1, and 2 mm that they attribute to free-free emission from a cool ($\sim10^4$ K) stellar wind. These observations were made with the James Clerk Maxwell Telescope, and at their low levels of significance (a few standard deviations), combined with the difficulty in distinguishing between weak signals and fluctuations in sky opacity with single-dish telescopes, must be regarded as tentative. Mullan et al. (1992) nonetheless argued that the millimeter emission of YZ Canis Minoris (regarded as their most significant example), as well as a number of other dMe flare stars, is consistent with a radio spectrum that extended from centimeter to micron wavelengths with a spectral index of $\sim$0.7, as is expected from the theory for free-free emission by a fully ionized isothermal stellar wind. This is despite the fact that the centimeter emission of YZ CMi (and other flare stars) is often highly time-variable and can show high degrees of circular polarization, characteristic of nonthermal flares and contrary to the properties expected of a stellar wind. From the measured millimeter flux, Mullan et al. (1992) inferred a mass-loss rate for YZ CMi of $\sim5\times10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, more than 4 orders of magnitude higher than that of the Sun. Such a high mass-loss rate sustained over an extended period would have important evolutionary consequences for a low-mass star.

Motivated in part by the above report, we have used the Berkeley-Illinois-Maryland Association (BIMA) Array at millimeter wavelengths to observe YZ CMi. We also observed the dMe flare star AD Leonis, which shows perhaps the best evidence thus far for CMEs on active late-type dwarf stars (Houdebine, Foing, & Rodonó 1990). The advantages of using an aperture-synthesis array rather than a single dish for radio observations of compact sources such as active stars have been well documented: interferometer observations are less sensitive to fluctuations in atmospheric attenuation, and they yield a high-resolution image which offers unequivocal discrimination between a compact stellar source and other sources that may act as a source of confusion for single-dish telescopes. To the best of our knowledge, this Letter presents the first reported aperture-synthesis observations of active late-type stars at short millimeter wavelengths. In § 2 we describe our observations and results. In § 3 we compute from the data at millimeter and, in particular, longer radio wavelengths limits on the mass loss from YZ CMi and AD Leo associated with a steady, spherically symmetric stellar wind; these computations are widely applicable to all active late-type dwarf stars. In § 4 we examine the contrasting case where sporadic, non–spherically symmetric outflows, perhaps analogous to solar CMEs, can contribute to the mass loss of active late-type dwarf stars. Finally, in § 5 we summarize our conclusions.

2. OBSERVATIONS AND RESULTS

We observed YZ CMi on 1995 September 3, and AD Leo on September 5. At the time the BIMA Array comprised six antennas, which were then arranged in their most compact configuration. The correlator was configured to give a maximum bandwidth of 800 MHz centered at 3.5 mm (86 GHz). Our observations of each star spanned $\sim$8 hr, which comprised alternate 15 and 4 minute scans, respectively, of the star and a secondary (phase) calibrator (0739+016 for YZ CMi and 0956+252 for AD Leo). Planets were observed for primary flux calibration. Observing conditions were apparently good, and the instrumental and atmospheric phase corrections required for calibration varied only slowly through each observation. We are therefore confident that decorrelation due to poorly calibrated phases was not a problem for these observations.

An image was made of each field extending beyond the primary beam ($\sim150''$). The size of the deconvolved (clean) beam was $14''.5\times9''.0$ for YZ CMi and $13''.6\times9''.4$ for AD Leo. No sources were detected in either field. From the images we derive 3 σ upper limits of 10 mJy for the flux density of each star.

3. LIMITS ON SPHERICALLY SYMMETRIC MASS LOSS: STELLAR WINDS

3.1. *Constraints from Millimeter Observations*

Mullan et al. (1992) reported the (tentative) detection of YZ CMi at 1.1 mm with a flux density of 13.2 ± 6.0 mJy. If this detection is valid and if the emission originates from a stellar wind, then (using their derived spectral index of 0.7) YZ CMi should have a flux density at 3.5 mm of 5.9 ± 2.7 mJy. This is compatible with our inferred upper limit. Because our observation places a definitive upper limit on any 3.5 mm emission from YZ CMi and AD Leo, we can derive formal upper limits on their mass-loss rates. The 86 GHz flux density from a spherically symmetric, constant-velocity, optically thick wind on a star with an ionized mass-loss rate $\dot{M}$ is (from Panagia & Felli 1975 and Wright & Barlow 1975)

$$S\approx25\left(\frac{\nu}{86\ \mathrm{GHz}}\right)^{0.6}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{0.1}\left(\frac{\dot{M}}{10^{-10}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{4/3}\times\left(\frac{v_\infty}{300\ \mathrm{km\ s^{-1}}}\right)^{-4/3}d_{\mathrm{pc}}^{-2}\ \mathrm{mJy}, \quad (1)$$

where v_∞ is the terminal velocity of the wind, T the temperature of the wind, and d_{pc} the distance to the star in parsecs. For $v_\infty\approx300$ km s^{-1}, as assumed by Mullan et al. (1992), the mass-loss rate of YZ CMi (6.0 pc distant) from a $\sim10^4$ K wind cannot exceed $9\times10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. For AD Leo (4.9 pc), the corresponding upper limit is $6\times10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. We show below that existing observations at longer radio wavelengths already place—albeit indirectly—a much lower upper limit on the mass-loss rate of winds on active late-type dwarf stars.

3.2. *Constraints from Detectability of Coronal Radio Flares*

Incoherent and/or coherent nonthermal radio emission have been observed from active late-type dwarf stars spanning the spectral class range G–M. This emission, by analogy to the Sun, is attributed to accelerated electron populations gyrating in strong coronal magnetic fields located close to the stellar surface. Evidence for relatively compact radio coronae on dMe flare stars comes from direct imaging using VLBI, which indicates that nonthermal radio sources on YZ CMi (Benz & Alef 1991), AD Leo, and EQ Peg B (Benz, Alef, & Güdel 1995) cannot be significantly larger than the stellar disk. Observations of rotationally modulated radio emission from the K and G dwarf stars AB Doradus (Lim et al. 1992, 1994) and EK Draconis (Güdel et al. 1995), respectively, further imply that the radio source must be located close to the stellar surface.

To be detectable, the radiation from coronal radio sources must be able to propagate outward from the star without being absorbed by a wind. The radius at which a spherically symmetric stellar wind becomes optically thick ($\tau = 1$) at a frequency ν may be derived from the expression

$$\frac{R(\nu)}{R_\odot} \approx 6\left(\frac{\nu}{10\ \mathrm{GHz}}\right)^{-2/3}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1/2} \times \left(\frac{\dot{M}}{10^{-10}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{2/3}\left(\frac{v_\infty}{300\ \mathrm{km\ s}^{-1}}\right)^{-2/3}. \quad (2)$$

Any observed nonthermal emission from a star with such a wind must originate from above the optically thick surface in the wind at the observing frequency. If YZ CMi has the wind parameters inferred by Mullan et al. (1992), then the optically thick surface of its wind at 10 (1) GHz would lie at a radius of $\sim$50 (200) R_* ($R_* \approx 0.37\ R_\odot$). Observations of the Sun and theoretical considerations imply that nonthermal radio emission in this frequency range requires magnetic fields of order at least 100 G or relatively high coronal plasma densities of order 10^{10} cm^{-3}, conditions met in the corona only close to the stellar surface, in agreement with the observations cited above. If instead the magnetic field is as large as 100 G at 50–200 R_*, then even if we assume that it has a dipolar dependence (which gives the slowest falloff allowed for magnetic fields at large radii), a photospheric magnetic field strength of 10^7–10^9 G is required. This is up to 5 orders of magnitude stronger than the observed surface fields on dMe flare stars. This argument, in combination with the evidence cited above that the nonthermal radio sources lie close to the stellar surface, clearly shows that the wind properties inferred by Mullan et al. (1992) are inconsistent with the observation of nonthermal radio emission from dMe flare stars.

We can tightly constrain the ionized mass-loss rate from active late-type dwarf stars by requiring that the wind be optically thin, i.e., that the optically thick surface lies below the stellar surface at all pertinent frequencies. Since the radius of the optically thick surface for a given mass-loss rate is larger at lower frequencies, the strongest constraint is provided by nonthermal flares detected at the lowest frequencies. The lowest frequency at which nonthermal radio emission has credibly been detected from active late-type dwarf stars is 327 MHz, seen from YZ CMi (Kundu & Shevgaonkar 1988). Setting $R(327\ \mathrm{MHz}) = R_*$, we find that a $\sim 10^4$ K, $\sim$300 km s^{-1} wind on YZ CMi must have $\dot{M} \leq 5 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$. The inferred upper limit is 4 orders of magnitude lower than the mass-loss rate derived by Mullan et al. (1992) from their 1.1 mm observations, and is comparable to the mass-loss rate of the Sun from its wind. Such a low mass-loss rate is consistent with that inferred for the dMe flare star Proxima Centauri by Lim, White, & Slee (1996), who, based on the low upper limit to the stellar flux density at 3.5 cm, directly placed an upper limit of $\sim 7 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$ on its mass-loss rate from a $\sim 10^4$ K, $\sim$300 km s^{-1} wind.

From equation (2) it is apparent that a hotter wind can have a higher mass-loss rate than a cooler wind but still remain optically thin. In the case of YZ CMi, a wind at $T \approx 10^6$ K and $v_\infty \approx 300$–600 km s^{-1} (parameters similar to the solar wind) must have $\dot{M} \leq 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$. This is more than an order of magnitude below the lower limit predicted by Badalyan & Livshits (1992) from their theoretical model. A hotter wind still at $\sim 10^7$ K could sustain $\dot{M} \leq 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ without affecting the visibility of radio emission in the low corona. We note that soft X-ray observations also can constrain the mass-loss rate from any stellar winds at $T \approx 10^6$–10^7 K. For YZ CMi, one can show that its soft X-ray parameters constrain the mass-loss rate from 10^6–10^7 K winds at solar-wind–like velocities to $\dot{M} \leq 6 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$, consistent with but less stringent than those implied by the visibility of radio emission from the low corona. Because current evidence indicates that the X-ray emission of late-type dwarf stars (like their nonthermal radio emission) originates predominantly from relatively compact coronal structures near the stellar surface, the constraints derived from their soft X-ray properties must be considered as extreme upper limits.

Our arguments are widely applicable to active late-type dwarf stars from which radio emission believed to originate from close to the stellar surface has been detected. In general, therefore, any wind on these stars at coronal temperatures of $\sim 10^6$ K and velocities of 300–600 km s^{-1} cannot have a mass-loss rate of more than $\sim 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$, about 2 orders of magnitude higher than the mass-loss rate of the Sun from its wind. Any cooler wind at $\sim 10^4$ K but with similar velocities cannot have a mass loss of more than $\sim 10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$, 3 orders of magnitude lower than that inferred by Mullan et al. (1992) to exist on dMe flare stars.

4. LIMITS ON ASYMMETRIC MASS LOSS: CORONAL MASS EJECTIONS

We consider now the contrasting case where mass loss takes place by sporadic, non–spherically symmetric events such as CMEs. On the Sun the CME outflow tends to occupy a cone of outgoing angles approximately 60° across, and hence an individual CME need not obscure a large fraction of the solar disk.

Mullan et al. (1989) discussed the possibility that the (cool) mass outflow inferred from the K dwarf in the V471 Tau system could be dominated by an ensemble of CMEs rather than a steady stellar wind. Cully et al. (1994) attributed a large flare detected in the extreme-ultraviolet (EUV) from the dMe flare star AU Microscopii to a massive CME (at $T \approx 10^7$ K), and pointed out that an ensemble of such randomly distributed CMEs could mimic the $\nu^{\sim 0.7}$ radio spectrum inferred by Mullan et al. (1992) for a number of dMe flare stars. To investigate whether CMEs could indeed be responsible for the millimeter detections reported by Doyle & Mathioudakis (1991) and Mullan et al. (1992), we note that the optical depth of a CME (which we approximate here as a cylindrical volume seen face-on) to free-free absorption is given by

$$\tau \approx 400\,\frac{\mathrm{EM}}{10^{53}\ \mathrm{cm}^{-3}}\,\frac{R_\odot^2}{A}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{-3/2}\left(\frac{\nu}{100\ \mathrm{GHz}}\right)^{-2}, \quad (3)$$

where $\mathrm{EM} = \int n_e^2\, dV$ cm^{-3} (n_e being the electron density and V the volume) is its (instantaneous) emission measure and A is its (instantaneous) cross-sectional area. Free-free emission has a ν^2 spectrum in the optically thick regime, and at a given frequency ν the flux density is

$$S \approx 4.9\,\frac{T}{10^4\ \mathrm{K}}\,\frac{R_{\mathrm{CME}}^2}{R_\odot^2}\left(\frac{\nu}{100\ \mathrm{GHz}}\right)^2 d_{\mathrm{pc}}^{-2}\ \mathrm{mJy}, \quad (4)$$

where R_{CME} is the cross-sectional radius of the CME. In this regime the flux density is independent of EM, and depends only on the temperature and projected area of the source. On the other hand, in the optically thin regime free-free emission has a flat spectrum (i.e., independent of frequency), and the source flux density depends on EM according to

$$S \approx 640 \frac{\mathrm{EM}}{10^{53}\ \mathrm{cm}^{-3}} \left(\frac{T}{10^4\ \mathrm{K}}\right)^{-1/2} d_{\mathrm{pc}}^{-2}\ \mathrm{mJy}. \quad (5)$$

One can estimate the flux density produced by the most massive possible CMEs on dMe flare stars by equating their emission measures to the peak emission measures of the most powerful soft X-ray flares seen on these stars, that is, EM $\approx 10^{53}$ cm^{-3} (e.g., Cheng & Pallavicini 1991). As the CME expands, its emission measure will drop, and so the peak emission measure used in the current example corresponds to the very start of a CME, when its projected area is comparable to or smaller than the stellar disk. Considering first CMEs at $T \approx 10^4$ K, one finds from equation (4) that a CME with EM $\approx 10^{53}$ cm^{-3} and $R_{\mathrm{CME}} \approx R_\odot$ is optically thick to over 1000 GHz, and at the distance of YZ CMi will have a flux density of ~1 mJy at a wavelength of 1 mm (300 GHz). As the CME expands, its flux density will increase so long as it remains optically thick, and in the current example it will attain a maximum flux density of ~2 mJy (when the CME has a radius of ~11 $R_\odot$, at which time $\tau \approx 1$). With further expansion its flux density will drop as EM decreases, since it is now optically thin. A CME with the same parameters as above but $T \approx 10^6$ K will be optically thin at the outset, and (at this time of maximum intensity) will have a flux density of ~2 mJy. Thus, CMEs in the temperature range 10^4–10^6 K (or higher) cannot explain the order of magnitude higher flux densities reported by Doyle & Mathioudakis (1991) and Mullan et al. (1992) at millimeter wavelengths from a number of dMe flare stars. Since CMEs may be optically thick at radio frequencies, however, they may produce observable effects by obscuring coronal radio emission for short periods of time when the viewing geometry is suitable.

As in the case of a stellar wind, the mass-loss rate from CMEs cannot be so high that, as an ensemble, they significantly absorb nonthermal radio emission from close to the stellar surface. We show from a simple qualitative argument that the upper limit thus placed on the mass-loss rate is no higher than in the case of a steady, spherically symmetric stellar wind. The difference between an ensemble of randomly distributed CMEs and a stellar wind with the same mass-loss rate and velocity is that in the former case matter is unevenly distributed with radius: effectively, CMEs consist of a number of relatively thin partial shells concentric with the star. From equation (3), it is clear that the opacity of a shell of given total mass increases if the shell is compressed, because $\tau \propto n_e^2$. Consequently, a given amount of mass unevenly distributed will always have higher opacity than the same amount of mass evenly distributed; i.e., a wind consisting of CMEs will have higher opacity than a steady stellar wind of the same velocity and mass-loss rate. Thus, even if CMEs have velocities somewhat higher than the stellar wind velocities assumed in the previous section, they cannot have a (time-averaged) mass-loss rate significantly higher than that inferred previously for a steady, spherically symmetric wind. Our stringent upper limit is consistent with previous estimates of the mass-loss rate from CMEs on active late-type dwarf stars. For example, interpreting the enormous EUV flare detected from AU Mic as an example of a long-duration CME, Cully et al. (1994) assumed a plausible event rate to estimate a mass-loss rate from CMEs of $\sim 10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$ on this star.

5. CONCLUSIONS

We have placed firm upper limits on the mass-loss rates by a stellar wind or coronal mass ejections on active late-type (G–K) dwarf stars. If the winds on these stars have velocities of 300–600 km s^{-1} and temperatures $\sim 10^6$ K, parameters similar to the solar wind, then their mass-loss rate cannot exceed $\sim 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$, about 2 orders of magnitude higher than the mass-loss rate of the Sun from its wind. A cooler wind at $\sim 10^4$ K but the same velocity cannot have a mass-loss rate higher than $\sim 10^{-13}\ M_\odot\ \mathrm{yr}^{-1}$. Coronal mass ejections, even if they have somewhat higher velocities, cannot have a time-averaged mass-loss rate significantly above the upper limit inferred for a stellar wind at the same temperature. We conclude that unless mass outflows from active late-type dwarf stars have velocities and/or temperatures very much higher than that seen on the Sun, their mass-loss rates cannot reach the levels of 10^{-11} to $10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ suggested by Mullan et al. (1992). Our arguments do not apply to any neutral component of the stellar wind, since it will be transparent to radio emission. From the absorbing neutral column densities to nearby dMe stars derived from X-ray and EUV observations, one can show that the mass-loss rate of any spherically symmetrical neutral wind must be less than $\sim 10^{-13}\ (v_\infty/300\ \mathrm{km\ s}^{-1})\ M_\odot\ \mathrm{yr}^{-1}$. It is generally assumed, however, that all of the neutral absorbing column can be attributed to the intervening interstellar medium and not to any stellar wind.

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