RADIO EMISSION FROM FLOWS

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Many emission line stars are radio sources including early type stars such as ζ Pup and P Cyg, peculiar objects such as MWC 349 (a possible proto-planetary system) and V1016 Cyg, nebular variables such as T Tau, and at least one late M giant. These "radio stars" are characterized by (1) a rising spectrum with spectral index $\alpha = 0.6$ to 1.1, (2) positional coincidence between star and radio source, and (3) no rapid (less than 10^7 sec) time variability. These characteristics are in contrast with the non-thermal spectrum and rapid variability of Algol type "radio stars" and the radio emission associated with x-ray sources. The radio component of the spectrum of emission line stars originates in the substantial mass loss flows which are a feature of their outer atmospheres and which, when ionized by stellar radiation, radiate by free-free electron thermal bremsstrahlung. These circumstellar H II regions are, in general, detectable with present radiotelescopes if the characteristic size of the optically thick region of the flow is greater than about 10^{-7} of the distance to the star.

In the radio emission region (typically at radii greater than a few A.U.), the flow has reached terminal velocity, V_∞, and thus the electron density varies as the inverse square of the radius. Wright and Barlow (1975) and Panagia and Felli (1975) have discussed emission from such flows and shown that the resulting spectral index is $\alpha = 0.6$. The mass loss rate may be calculated from the observed radio flux, S_ν, at frequency ν, the distance, d, and the terminal velocity:

$$\frac{dM}{dt} = 2.9 \times 10^{-9} \left[\frac{S_\nu}{\text{mJy}}\right]^{0.75} \left[\frac{d}{\text{kpc}}\right]^{1.5} \left[\frac{\nu}{10\ \text{GHz}}\right]^{-0.45} \left[\frac{V_\infty}{\text{km/s}}\right] M_\odot/\text{yr}$$

where it is assumed that the electron temperature is 10^4 K and understood that dM/dt refers only to the ionized component of the flow.

The mass loss rates derived from radio observations for both early type and other emission line stars for which reasonable distance and terminal velocity measurements or estimates are available are tabulated below. With the exception of BN Gem, for which there is only one λ = 13 cm observation from an NRL "radio star" survey conducted with the

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300 m antenna at Arecibo, Puerto Rico, all of these stars have constant, thermal (α = 0.6 to 1.1) spectra and thus the estimate of the mass loss rate is reliable to about ± 50%. If the BN Gem result is confirmed and its spectrum verified, it represents an example of a main sequence O star with a very large mass loss rate which may be contrasted with a negative result from the same survey for S Mon. Although several nearby emission line stars in NGC 2264 are radio sources (indicating mass loss rates of the order of 10^{-6} $M_{\odot}$/yr) S Mon (07n) is undetected at a flux level indicating a mass loss rate of less than 3 x 10^{-6} $M_{\odot}$/yr.

Stellar Mass Loss Rates Derived from Radio Observations

	Sp	d(kpc)	V_{∞}(km/s)	$\frac{dM}{dt}$ ($M_{\odot}$/yr)	
I. Early Type Stars					
BN Gem	08 V pec	1.61	500	13	1
γ Vel	WC8 + 09I	.45	2900	39	2
MWC 349	Be pec	2.1	100	67	3
P Cyg	Ble I	1.8	240	20	3
RY Sct	Be pec	2.0	30	18	4
ζ Pup	04 If	.45	2660	6.3	2
II. Other Stars					
α Ori	M2I	.2	10	.03	3
LkHα 101	Fe	.8	100	4.3	3
T Tau	Kle	.16	225	.37	3
V1016 Cyg	Me pec	1.4	105	6.8	3

References:

1. d: Barlow and Cohen (1977), V_{∞} assumed
2. Morton and Wright (1978)
3. Schwartz and Spencer (1977)
4. d, V_{∞}, flux: Hughes and Woodsworth (1973)

Although the stars listed above undoubtedly represent the upper bound mass loss rates for their respective types, the general statement can be made that mass loss rates are as high as 10^{-5} $M_{\odot}$/yr in some OB stars (peculiar objects such as MWC 349 have rates an order of magnitude greater) and mass loss rates are as high as 10^{-6} $M_{\odot}$/yr in some nebular variables. The latter result almost certainly reflects the fact that radiation pressure alone does not drive all flows and emphasizes the fact that high mass loss rates are a feature of the evolution of low to intermediate mass stars as well as of very massive stars. Despite the result for α Ori, which only relates to the unionized portion of the flow around a low temperature star, mass loss rates of the order of 10^{-6} $M_{\odot}$/yr are characteristic of most late M giants where the gas is coupled to the very

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intense infrared radiation field by dust (Gehrz and Woolf, 1971). In some late type stars, particularly those with circumstellar maser emission, even higher mass loss rates than those indicated for OB stars probably exist. Thus mass loss is also an important feature of post-main-sequence evolution. As new and more powerful observational instruments in the radio and infrared become available, mass loss and interaction between stars and the interstellar medium will probably be seen to be an even more important factor in evolution at many stellar masses and ages.

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DISCUSSION FOLLOWING SCHWARTZ

Conti: In reference to Billy Bidelman's comments earlier, we may have here another example of the nomenclature obscuring the physics; one should use both the HD name and variable star name together. I know about this star, BN Gem, discussed by Schwartz because I have spectra of it as HD 60848. The high mass loss rate may be related to its Oe type (analogous to Be classification), where rotation probably plays a role in the outflow.

Underhill: It's interesting that S Mon (=15 Mon) is not detected. It's a "well-behaved" near main sequence star.