RADIO OBSERVATIONS OF STELLAR MASS LOSS

Sun Kwok and C. R. Purton
C.R.E.S.S., York University,
Downsview, Ontario, Canada.

A program to search for steady-state thermal emissions from stars has been in progress for several years in Canada (Purton 1976). In this program we have specifically excluded flaring objects (such as β Lyr or HR1099) where non-thermal emission is probably responsible. Out of the 30 or so detections, about 1/4 of them show a ~+1 spectral index, suggesting a $1/r^2$ density profile in the emitting region. This implies the existence of a non-static circumstellar envelope which is mostly likely the result of continuous mass outflow.

In order for thermal emission from a stellar wind to be detectable, two conditions must be satisfied: a high emission measure and a source of ionization. In a stellar wind situation, the radio flux F_ν is proportional to $(\dot{M}/V)^{4/3}$ (Wright and Barlow 1975) where $\dot{M}$ is the mass loss rate and V the ejection velocity. The feasibility of studying stellar mass loss is therefore controlled by the mass loss mechanism.

Table 1
Mass Loss Mechanisms for Stars of Different Spectral Types

Mechanism	Spectral Type	$\dot{M}(M_\odot yr^{-1})$	$V(Kms^{-1})$
1. Radiation Pressure on Grains	Late Type Giants & Supergiants	$< L/Vc$ $\sim 10^{-6}-10^{-5}$	5-30
2. Radiation Pressure on Gas	O,B Supergiants, WR stars	$< NL/c^2$	500-1500
3. Mass Motions			
a. Coronal Evaporation	Lower MS stars	$\sim 10^{-14}$	~500
b. Macro-turbulence	G & K Supergiants e.g. HR8752 (G0Ia)	4×10^{-7}	~16
4. Radiation Pressure on Grains + Mass Motions	G, K, early M Super-giants e.g. HR5171 (G8Ia) μ Cep (M2Ia)	3×10^{-5} 10^{-5}	~14

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In table 1 we have outlined the major mass loss mechanisms for stars of different spectral types. Dust grains, having a continuum opacity to stellar radiation, can eject the atmosphere of cool luminous stars on a large scale and at a low velocity (Gilman 1972, Kwok 1975). In comparison, radiation pressure on ionized gas has a mass loss rate dependent on the number of resonance lines (N) and the ejection velocity is much higher. Mass loss processes which rely on energy input (e.g. the solar wind) rather than momentum input generally have a much lower mass loss rate. Macro-turbulence in the chromospheres of G and K supergiants are capable of increasing the atmospheric scale height to bring the gas to a point where the escape velocity is low, but this process is not very efficient. However if dust grains are condensed, they can greatly increase the atmospheric opacity and enhance the mass loss rate (Gilman and Woolf, unpublished manuscript).

We note that stellar winds ejected under radiation pressure on grains have a large $\dot{M}$ and small V and therefore should be the easiest to detect whereas stellar winds ejected by radiation pressure on gas have ejection velocities so high that the radio flux is expected to be very low unless the star is nearby.

As for sources of ionization, photo-ionization is easily achieved by the presence of a hot star. In some cases, a strong shock wave may be responsible.

By combining the respective mass-loss and ionization mechanisms we have attempted to classify the detected mass outflow radio stars into 5 types.

Class I	OB Supergiants, Wolf-Rayet stars: radiation pressure on ionized gas. Examples: P Cygni, γ^2 Vel, ζ Pup.
Class II	Binary (M giant + hot star): stellar wind from M giant ionized by hot companion. Example: AG Peg (M3III + WN6)
Class III	Mass loss and ionization by supersonic mass motions. Examples: HR8752 (G0 Ia), the sun.
Class IV	Young Stars: re-expansion of co-coon, dust and gas of the proto-stellar nebula ejected by radiation from the new born star. Examples: LHα 101, MWC 349 (?)
Class V	Very young Planetary Nebulae: Ionization of the remnant red-giant envelope through exposure of hot core. Examples: V1016 Cygni, HM Sge.

Although the number of stars belonging to Class I is large, yet the expected radio flux is low for reasons given above. Class II represents a subset of symbiotic stars which have been extensively searched and resulted in a number of detections (Wright and Allen 1978). Although late-type supergiants have large $\dot{M}/V$ but normally the outflowing material is neutral, therefore explaining the low search success rate (Smolinski et al. 1977). Post-shock heating due to large scale mechanical motion in the outer-atmosphere may ionize part of the stellar wind and lead to radio emission. The large turbulent velocity (38 km s^{-1}) observed in the only detected cool supergiant (HR8752) is consistent with this suggestion. HR5171 having a turbulent velocity of 50-100 km s^{-1} may also be a good candidate for future observations.

The most interesting category resulting from our study of radio stars is Class V. Continuous mass loss in the red-giant stage is expected to eventually deplete the hydrogen atmosphere and expose the hot core. The change in stellar surface temperature leads to a change in mass loss mechanism from radiation pressure on grains to radiation pressure on gas, resulting in a large increase in ejection velocity. The collision of the new high velocity wind with the remnant red giant wind will create a high density shell which in time will develop into a planetary nebula (Kwok, Purton and FitzGerald 1978, Kwok and Purton 1978). In very young planetary nebulae where the old wind has not yet been totally swept up by the shell, thermal emission from the old wind will be produced as a result of its ionization by the exposed hot core.

There is a group of radio stars (H1-36, VY2-2, Hb12, Hen1044, He2-90) whose nature we are uncertain of. Their spectra are similar to V1016 Cygni and HM Sge, having a +1 spectral index at low frequency and becoming optically thin between 10-100 GHz. This implies that the base of the outflow has a radius 10^{14} - 10^{15} cm, much larger than the size of a star. The existence of such a large bubble is difficult to understand although it is consistent with the properties of very young planetary nebulae where the base of the remnant red-giant wind is detached from the star.

In conclusion the nature of radio stars undergoing mass loss is very diverse and they do not form an homogeneous group. Mass loss from OB supergiants, having a high ejection velocity, only emit weakly in the cm region and are not particularly suitable for study in the radio.

References

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DISCUSSION FOLLOWING KWOK AND PURTON

Noerdlinger: Dust is observed in planetary nebulae, often fairly deep inside. There are theories for formation of dust grains in such hot winds, but I wonder if an instability could develop at the interface of the two winds leaving inclusions behind so the existing dust grains could act as nuclei for new ones?

Kwok: In our examples of very young planetary nebulae V 1016 Cygni and HM Sge, both show two dust components. One is the silicate component which is probably the remnant of the progenitor red giant. Another is a featureless 1000 K blackbody similar to dust grains observed in say Nova Vul. We interpret this hot dust component (possibly graphite) to be recently formed after the exposure of the hot core. In several hundred years, the silicate feature will disappear and the new grains will dominate the IR spectrum as we observe in planetary nebulae. For instability we are currently investigating this possibility for it may explain the presence of condensations in planetary nebulae. Dust grains are seen to be forming near the nuclei of planetary nebulae A 30 and A 78 (Cohen and Barlow, Ap. J. 193, 401). If this is true, then it is unlikely that old grains serve as nuclei for new grains. Also dust grains seem to be able to condense around novae with no problem.