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ON THE INTENSITY AND SHAPE OF RADIO RECOMBINATION LINES FROM IONIZED STELLAR WINDS

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RESUMEN

Los vientos ionizados de las estrellas de tipo temprano emiten radiación continua (libre-libre) que ha sido detectada en el radio para un número apreciable de estrellas. La medición de esta emisión continua permite una determinación confiable del cociente de la tasa de pérdida de masa a la velocidad terminal del viento, $\dot{M}/V_\infty$. Estos vientos deben emitir también líneas de recombinación de radio muy débiles y anchas. La detección de estas líneas permitiría la determinación de V_∞ y $\dot{M}$ separadamente. Calculamos la intensidad y perfil esperados para este tipo de líneas. Para vientos típicos las líneas son demasiado débiles y anchas para ser detectadas con la instrumentación disponible actualmente. Sin embargo, vientos con velocidades terminales peculiarmente bajas podrían emitir líneas detectables. En particular, recientemente se detectaron líneas de recombinación de radio en MWC 349. Discutimos las características de las líneas de esta fuente.

ABSTRACT

The ionized wind of early-type stars emit continuum (free-free) radiation that has been detected in the radio frequencies for an appreciable number of stars. The measurement of this continuum emission allows a reliable determination of the ratio of mass-loss rate to wind terminal velocity; $\dot{M}/V_\infty$. These winds should also emit very weak and wide radio recombination lines. The detection of these lines would allow a determination of V_∞ and $\dot{M}$ separately. We calculate the expected intensity and shape of these lines. For typical winds the lines are too weak and wide to be detected with presently available instruments. However, stellar winds with peculiarly low terminal velocities may have detectable radio recombination line emission. In particular, lines have been detected recently in MWC349. We discuss the line characteristics of this source.

Key words: LINES-STARS – RADIO SOURCES – WINDS

I. INTRODUCTION

The basic parameters that characterize a stellar wind are the mass-loss rate, $\dot{M}$, and the wind terminal velocity, V_∞. In the case of early-type stars the winds are expected to be fully ionized to infinity (Panagia and Felli 1975; Wright and Barlow 1975; Olnon 1975), and free-free emission can be detected for some stars in the radiofrequencies (Braes, Habing and Schoenmaker 1972; Abbott *et al.* 1980). Unfortunately, the parameter that can be obtained from the radio continuum measurements is a composite one; $\dot{M}/V_\infty$. Usually, a value of V_∞ from optical or UV observations is adopted and $\dot{M}$ can be derived. However, it is unclear whether the terminal velocity measured from optical or UV lines is still the same as the velocity at the large distances where the radio emission is generated (Florkowski and Gottesman 1977). In this paper we discuss the possibility of detecting radio recombination lines from ionized stellar winds. These lines originate far from the stellar surface and allow a very reliable determination of V_∞.

II. THE MODEL

Following Panagia and Felli (1975) we will assume that the wind is isothermal and isotropic with an electron density given by

$$n_e = n_0 \left(\frac{r}{r_0} \right)^{-2} , \tag{1}$$

where r is the radius of the point considered, r_0 is the stellar radius, and n_0 is the electron density at r_0. Then, the continuum (free-free) flux is given by (Panagia and Felli 1975):

$$S_C(\nu) = 2\pi \frac{{r_0}^2}{d^2} \; B(\nu) \int_0^\infty (1 - e^{-\tau_C(\xi)})\xi \, d\xi \; . \tag{2}$$

In this equation ν is the frequency of observation, d is the distance to the star, $B(\nu)$ is Planck's function, $\tau_C(\xi)$ is the continuum optical depth at ξ, and ξ is the projected radius in units of r_0 (see Figure 1). Equation (2) gives

$$S_C(\nu) = 5.57 \frac{{r_0}^2}{d^2} \; \pi B(\nu) \left[\frac{\pi}{6} \; n_0^2 \, r_0 \, \kappa_C(\nu) \right]^{2/3} \tag{3}$$

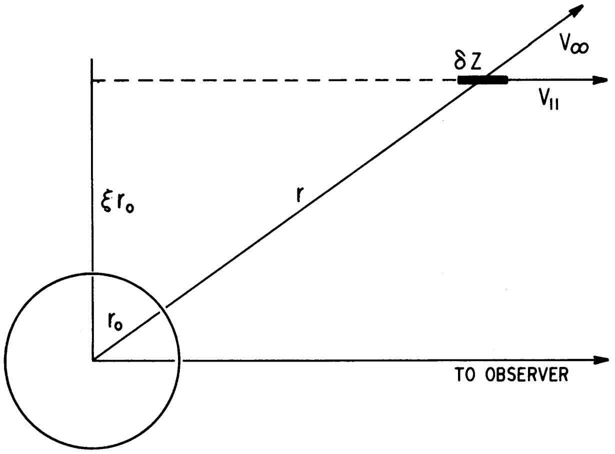

Fig 1. The geometry of the model. r_0 is the stellar radius, ξ is the projected radius in units of r_0, r is the radius of the point considered, δz is the correlation length, V_∞ is the terminal velocity of the wind and $V_{||}$ is the component of V_∞ in the observer's line of sight.

where $\kappa_C(\nu)$ is the absorption of the continuum, that in the radio range is given by (Mezger and Henderson 1967):

$$\kappa_C(\nu) \simeq 8.4 \times 10^{-28} \left[\frac{\nu}{10\ \mathrm{GHz}}\right]^{-2.1} \left[\frac{T_e}{10^4 \mathrm{K}}\right]^{-1.35} . \quad (4)$$

T_e is the electron temperature. We will assume that, at a given point, the line emission has a Gaussian profile with a full width at half intensity, ΔV, much smaller than the wind's terminal velocity V_∞, that is, $\Delta V \ll V_\infty$. Since the electron temperature of the wind is expected to be about 10^4 K, $\Delta V \sim 10$ km s^{-1}, which is a value much smaller than typical wind terminal velocities, $V_\infty \simeq 10^2 - 10^3$ km s^{-1}. This assumption allows to approximate the optical depth in the line by

$$\tau_L(\nu, V_{||}) = n_e^2\, \delta z\, \kappa_L(\nu) , \quad (5)$$

where $V_{||}$ is the component of V_∞ in the observer's line of sight, δz is the correlation length (Morris 1975) given by

$$\delta z = 1.06\, r_0\, \xi \frac{\Delta V}{V_\infty} \left[1 - \left(\frac{V_{||}}{V_\infty}\right)^2\right]^{-3/2} . \quad (6)$$

The 1.06 factor appears because we assumed a local Gaussian profile, while Morris assumed a local rectangular profile. Finally, $\kappa_L(\nu)$ is the absorptivity in the center of the line for an α radio recombination line, given approximately by (Dupree and Goldberg 1970):

$$\kappa_L(\nu) \simeq$$
$$1.9 \times 10^{-29} \left[\frac{\Delta V}{10^2\ \mathrm{km\ s^{-1}}}\right]^{-1} \left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-2.5} \left[\frac{\nu}{10\ \mathrm{GHz}}\right]^{-1} . \quad (7)$$

The assumption of a pure hydrogen wind is implicit in equation (5) and that of local thermodynamic equilibrium in equation (7). The line plus continuum flux is then given by

$$S_{LC}(\nu, V_{||}) =$$
$$2\pi \frac{r_0^2}{d^2} B(\nu) \int_0^\infty (1 - e^{-\tau_{LC}(\xi, V_{||})})\, \xi\, d\xi , \quad (8)$$

where

$$\tau_{LC}(\xi, V_{||}) = \tau_L(\xi, V_{||}) + \tau_C(\xi) . \quad (9)$$

From equations (1), (5) and (6) we obtain

$$\tau_L(\xi, V_{||}) =$$
$$1.06\, n_0^2 \frac{r_0^4}{r^4}\, r_0\, \xi \frac{\Delta V}{V_\infty} \left[1 - \left(\frac{V_{||}}{V_\infty}\right)^2\right]^{-3/2} \kappa_L(\nu) . \quad (10)$$

From the geometry of Figure 1 one finds

$$r = \xi\, r_0 \left(1 - \frac{V_{||}^2}{V_\infty^2}\right)^{-1/2} , \quad (11)$$

that substituted in (10) gives

$$\tau_L(\xi, V_{||}) = 1.06 \frac{n_0^2\, r_0}{\xi^3} \frac{\Delta V}{V_\infty} \left[1 - \left(\frac{V_{||}}{V_\infty}\right)^2\right]^{1/2} \kappa_L(\nu) . \quad (12)$$

Again, following the reasoning of Panagia and Felli (1976), equation (8) gives

$$S_{LC}(\nu, V_{||}) = 5.57 \frac{r_0^2}{d^2} \pi B(\nu)$$
$$\times \left[\frac{\pi}{6} n_0^2\, r_0\, \kappa_C(\nu) + 1.06 \frac{n_0^2\, r_0}{3} \kappa_L(\nu) \frac{\Delta V}{V_\infty} \times \left(1 - \left(\frac{V_{||}}{V_\infty}\right)^2\right)^{1/2}\right]^{2/3} . \quad (13)$$

Consequently, the line to continuum ratio is given by

$$\frac{S_L(\nu, V_{||})}{S_C(\nu)} = \frac{S_{LC}(\nu, V_{||}) - S_C(\nu)}{S_C(\nu)} . \quad (14)$$

In the microwave range and for typical parameters of ionized gas we have

$$\frac{\pi}{6} \kappa_C(\nu) \gg \frac{1.06}{3} \kappa_L(\nu) \frac{\Delta V}{V_\infty} , \quad (15)$$

which allows equation (13) to be expanded in a Taylor series. Finally equation (14) gives

$$\frac{S_L(\nu, V_{\parallel})}{S_C(\nu)} = 1.0 \times 10^{-2} \times \left[\frac{V_\infty}{10^2\ \mathrm{km\ s^{-1}}}\right]^{-1} \left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-1.15} \left[\frac{\nu}{10\ \mathrm{GHz}}\right]^{1.1} \times \left[1 - \frac{V_{\parallel}^2}{V_\infty^2}\right]^{1/2} ; \quad \text{for } \Delta V \ll V_\infty \tag{16}$$

The resulting profile is elliptical and the line-to-continuum ratio has the same temperature and frequency dependence of an optically thin H II region. The terminal velocity of the wind would simply be one-half the full width at zero power of the line.

III. DISCUSSION AND CONCLUSIONS

Are the lines from the wind of a typical early-type star detectable? From the results of Abbott *et al.* (1980), we expect $S_C(10\ \mathrm{GHz}) \simeq 3\mathrm{mJy}$, for $V_\infty \simeq 10^3\ \mathrm{km\ s^{-1}}$. Adopting $Te = 10^4$ K we obtain $S_L(10\ \mathrm{GHz}, V_{\parallel} = 0) \simeq 3 \times 10^{-3}$ mJy. This line intensity is far below that of the weakest lines detected. Furthermore, the width of the line, $\sim 2000\ \mathrm{km\ s^{-1}}$, is larger than the typical bandwidths of microwave spectrometers, which usually are less than $\sim 1000\ \mathrm{km\ s^{-1}}$. However, peculiar stars with low-velocity winds may be detectable. In particular, Altenhoff, Strittmatter and Wendker (1981), recently detected radio recombination lines from MWC349. In their analysis of the lines, they assumed that the local velocity dispersion, ΔV, was larger than the wind's terminal velocity, V_∞, that is, $\Delta V \gg V_\infty$. This assumption is the opposite to the one made by us, $\Delta V \ll V_\infty$. In typical stellar winds it is most probable that $\Delta V \ll V_\infty$ is the correct assumption. However, for MWC349, $V_\infty \simeq 50\ \mathrm{km\ s^{-1}}$ (Hartmann, Jaffe and Huchra 1980), and it is unclear which of the two assumptions is the more adequate. Furthermore, we could well be in the transition regime where $\Delta V \approx V_\infty$. Altenhoff, Strittmatter and Wendker (1981) show that for $\Delta V \gg V_\infty$, the line-to-continuum ratio is 2/3 that of the optically thin case. In our notation we have

$$\frac{S_L(\nu, V_{\parallel})}{S_C(\nu)} = 1.5 \times 10^{-2} \times \left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-1.15} \left[\frac{\nu}{10\ \mathrm{GHz}}\right]^{1.1} \left[\frac{\Delta V}{10^2\ \mathrm{km\ s^{-1}}}\right]^{-1} \times \exp\left(-4 \ln 2\, (V_{\parallel}/\Delta V)^2\right) ; \quad \text{for } \Delta V \gg V_\infty \ . \tag{17}$$

In this case the profile is Gaussian, and it does not contain information about V_∞. In Figure 2 we show the profiles expected under each assumption, for the same continuum flux. Unfortunately, given the weakness of the lines observed by Altenhoff, Strittmatter and Wendker (1981), it is not feasible to distinguish if the profile from MWC349 is elliptical or Gaussian. Furthermore, it is not possible to distinguish between models on the basis of integrated line flux, since both models predict the same integrated line flux. From (16) and (17) we have that for the same continuum flux:

$$\left[\int_{-\infty}^{\infty} S_\nu(\nu, V_{\parallel})\, dV_{\parallel}\right]_{\Delta V \gg V_\infty} = \left[\int_{-\infty}^{\infty} S_\nu(\nu, V_{\parallel})\, dV_{\parallel}\right]_{\Delta V \ll V_\infty} .$$

This equality can be understood qualitatively as follows. Consider a small volume at a given radius. In the case $\Delta V \gg V_\infty$, the line emission of this volume will contribute to the observed profile over all the velocity range, affected by the line-of-sight free-free processes. In the case $\Delta V \ll V_\infty$, the line emission of the small volume will contribute mainly to a given velocity of the observed profile, being again affected by the same line-of-sight free-free processes. Thus, while the respective line profiles are different, the *integrated* line profiles will be equal for both regimes. This also implies that in the transition regime, where $\Delta V \simeq V_\infty$, the integrated line profile will be the same and the profile will be intermediate between a Gaussian profile and an elliptical one. Thus, to distinguish if in MWC349 the width of the radio recombination lines is dominated by the local dispersion, the wind terminal velocity, or a combination of both, a profile with high signal-to-noise ratio is required.

Another interesting result is that the velocity of the center of the recombination line coincides with the

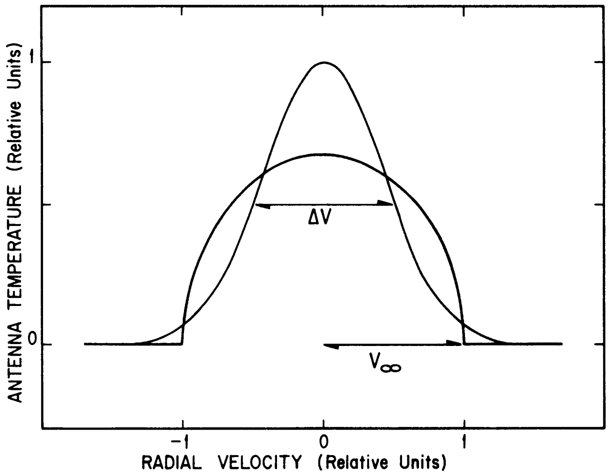

Fig 2. Expected profiles for radio recombination lines from ionized stellar winds in the cases $\Delta V \gg V_\infty$ (Gaussian profile) and $\Delta V \ll V_\infty$ (elliptical profile).

radial velocity of the star. Intuitively, one would expect to see a blueshifted profile since part of the line emission is coming from regions of high optical depth, apparently favoring the contribution of the foreground gas. However, the assumption of constant and common excitation temperature for line and continuum makes the optical depths to be additive, that is, the total optical depth along a given line of sight is the sum of the partial optical depths regardless of their relative positions. This makes the redshifted and blueshifted gas to contribute equally to the observed profile, resulting in a symmetric, non-shifted profile.

In conclusion, the spectral information contained in the radio recombination lines emitted by an ionized stellar wind could allow a reliable determination of the terminal velocity of the wind and of the radial velocity of the star. In combination with a continuum measurement, accurate mass-loss rates and electron temperatures could also be derived. Unfortunately, the lines are too weak and wide to be detected with present instruments. In the case of MWC349, the low terminal velocity of its wind permitted the detection of radio recombination lines at Bonn (Altenhoff, Strittmatter and Wendker 1981). Whether the width of the radio lines is dominated by local dispersion or by the wind's terminal velocity, could be decided by determining if the profile is Gaussian or elliptical.

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