Sound waves in stars and mass loss

ABSTRACT

It is generally agreed that the radiative forces on dust alone cannot drive the observed mass loss from Miras and other AGB stars. When combined with radial pulsations, dust can drive the mass loss provided that the dust forms sufficiently close to the star. Pijpers and Hearn (1989) have suggested that the mass loss is driven by high frequency sound waves. Dust is not necessary for this mechanism to work, and the formation of dust does not impede it. Wood (1990) has argued that the observations show that the dust forms too far away from the stars for radial pulsations to drive the mass the mass loss. His criticisms of the theory of Hearn and Pijpers (1989) applied to radially pulsating Miras are shown not to be relevant.

INTRODUCTION

It was first shown quantitatively by Kwok (1975) that dust formed in the wind of an AGB star could drive the wind. The dust grains are accelerated by the absorption of the radiation from the photosphere of the star and the collisions between the dust grains and the gas accelerate the gas. For most of the AGB stars dust does not form at the photosphere, but at a distance of several stellar radii. If the photosphere of the star is in hydrostatic equilibrium, the density of matter so far from the star is so small that the stellar wind that is driven is quite negligible. A second mechanism is necessary to bring sufficient material up to the region where the dust can form. Because Miras are radial pulsators, the favourite second mechanism has been radial pulsations. This was suggested initially by Hill and Willson (1979) and Wood (1979). More detailed calculations have been done by Bowen (1988). See also the contribution of Bowen to this workshop. The work of Bowen shows that if the dust can form at two stellar radii from the star then the combined radial pulsation dust driven winds can explain the observed mass loss from Miras.

Hartmann and MacGregor (1980) proposed a mechanism of driving mass loss from late type stars by Alfvén waves. If the Alfvén waves are not dissipated the winds produced are fast, that is the final velocity of the wind is greater than the escape velocity from the surface of the star. The winds observed from late type supergiants are slow, with a final velocity typically equal to half the escape velocity from the surface of the star. If the dissipation length of the Alfvén waves is about one stellar radius, then the final velocity of the Alfvén wave driven wind can be reduced to agree with the observations, but then no suitable dissipation mechanism is known and the final velocity of the wind is extremely sensitive to the details of the dissipation length (Holzer, Flå, and Leer, 1983).

MASS LOSS DRIVEN BY SOUND WAVES

Pijpers and Hearn (1989) have proposed a mechanism of driving winds from late type giants and supergiants by sound waves. This has been applied to mass loss from AGB stars by Pijpers and Habing (1989). This mechanism is not a coronal mechanism, but uses the gradient of the pressure of the sound waves to drive the wind, in the same way as the theory of Hartmann and MacGregor (1980) uses the gradient of the pressure of the Alfvén waves. A hot coronal wind is driven by the gradient of the gas pressure; the gas pressure is a measure of the thermal energy content of the gas coming from the kinetic motions of the atoms. The wave pressure is a measure of the internal energy of the gas resulting from the wave motions. The time dependent equation of hydrodynamics is non-linear. If the equation is averaged over many wave periods, the resulting average is not zero. An extra term appears in the stationary equation of motion and this is the gradient of the wave pressure. A common misconception is that a wave can only drive a wind by this mechanism if it is dissipated by some mechanism. This is not so. It works efficiently even though the wave is not dissipated. The theory of Pijpers and Hearn (1989) is then a stationary, linearised theory.

The important assumptions made in the theory are :-

- spherical symmetry
- radial flow
- sound wavelength $\ll$ scale height in the wind

(about a stellar radius)

- perfect gas
- no viscosity, magnetic field or radiative forces
- stellar atmosphere is isothermal
- sound waves are isothermal or adiabatic
- the dissipation length is constant throughout the atmosphere and specified

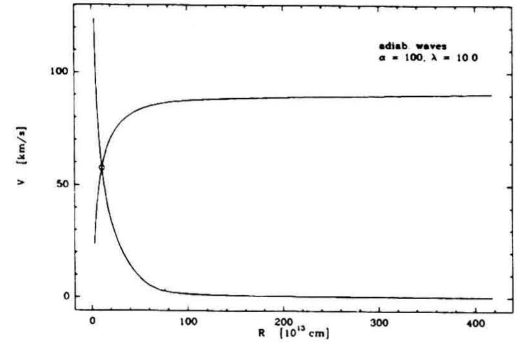

Figure 1: Wind velocity is plotted against distance for a sound wave driven wind

The combination of the equations of motion and continuity gives a Parker type solution. Extra terms from the wave pressure contribution can give three critical points instead of one when the dissipation length of the sound waves is short.

The input parameters to the models are the flux of sound waves and their dissipation length. The final velocity of the wind produced by this mechanism is less than the escape velocity from the surface of the star. Figure 1 shows the velocity distribution for one of the calculations with a sound wave dissipation length of 100 stellar radii. This calculation is for a star of 16 solar masses and 400 stellar radii. The escape velocity from the surface of the star is 123.5 km s^{-1}. The velocity of sound is 14.4 km s^{-1}. This velocity distribution is for adiabatic waves. The difference between adiabatic and isothermal waves is small. The final velocity of the wind driven by sound waves is much smaller than the final velocity of similar models driven by Alfvén waves because the sound velocity is much less than the Alfvén velocity.

Unlike the pulsation models calculated by Bowen (1988), dust is not necessary to drive the mass loss in the sound wave driven mechanism. If dust forms in the supersonic region of the flow it will increase the final velocity, but will have little effect on the mass loss.

The mechanism for driving the wind is the transfer of momentum from the sound wave flux to the mass flux. The analogy can be usefully drawn with the radiative driven winds described by Castor, Abbott and Klein (1975). Through the absorption of resonance line photons by the gas with the subsequent scattering of the radiation, the momentum of the photon is transferred to the gas. Similarly through the propagation of sound waves in the accelerating wind, momentum is transferred from the sound wave quanta to the gas. The picture is much more complicated than in the radiative driven winds because the velocity of light is independent of the gas velocity, whereas in the sound wave driven winds the sound waves are propagating with the speed of sound in the frame of reference moving with the wind.

Table 1 shows the mass loss $\dot{M}$ in solar masses per year and final velocity v_∞ in km s^{-1} of the wind driven by a flux F_m of sound waves from a star of 1.2 solar masses and 270 solar radii. The effective temperature is 3000 K. These are the same stellar parameters as those used by Bowen (1988). The total radiative flux of the star is 4.6 10^9 erg $cm^{-2}s^{-1}$. The sound waves are adiabatic and the sound speed is 5.7 km s^{-1}. The dissipation length of the sound waves in stellar radii is λ and $\sqrt{\langle \delta u^2 \rangle_o}$ is the mean square amplitude of the sound waves at the bottom of the wind.

This table shows that a flux of sound waves can drive a mass loss efficiently.

Table 1:

F_m erg cm^{-2} s^{-1}	λ	$\sqrt{\langle \delta u^2 \rangle_o}$ km s^{-1}	$\dot{M}$ $M_\odot$/year	v_∞ km s^{-1}
1.32 10^4	∞	0.03	1.87 10^{-7}	21.2
1.15 10^6	∞	0.3	1.41 10^{-5}	22.7
2.77 10^5	5.0	0.15	3.29 10^{-6}	14.6
1.92 10^7	5.0	1.3	2.06 10^{-4}	15.8

DISCUSSION

Wood (1990) raised two objections to this mechanism. Firstly that Miras undergo a strong radial pulsation, and that all times there exists in the photosphere material falling inward supersonically onto a shock front which is itself moving outward. Sound waves propagating outward from the interior will be blocked at this shock front and presumably reflected back into the star, thus preventing the dissipation required in the upper layers to produce mass loss.

Neither of these arguments is valid. Sound waves are propagating at the velocity of sound in the moving frame of the atmosphere. If this frame is moving up and down at supersonic velocities, this does not impede the progress of the sound waves in that moving frame. Eventually the sound waves will come to the top of the moving atmosphere. Nor are the sound waves reflected by a shock moving in the other direction. Landau and Lifshitz (1959) have shown that a sound wave cannot be reflected by an approaching shock because the shock wave is propagating with a supersonic velocity relative to the gas in front of it. The sound wave is instead strongly amplified by its passage through the shock. This phenomenon is known in other fields, for example the intense amplification of sound waves and magneto-acoustic waves by the Earth's bow shock.

SOUND WAVES OR RADIAL PULSATIONS?

Isothermal pulsations extend the atmosphere, but they do not drive a significant mass loss. Dust must form sufficiently close to the star where the densities are large enough to give the mass loss. Sound waves will drive a wind in the absence of dust, and the formation of dust does not impede the mechanism.

A crucial question is where does the dust form. Wood (1990) has argued that many studies of the flux distribution emitted by circumstellar dust round Mira and OH-IR stars show dust forming with temperatures of less than 1000 K. In his calculations of the mass loss driven by radial pulsations, Bowen (1988) assumes that the dust forms at 1500 K. This gives the dust forming at 2 stellar radii. If the dust forms at 1000 K the distance is increased to 4.5 stellar radii. Since the density scale height in the pulsation models is about 0.1 stellar radii the mass loss is reduced by ten orders of magnitude and cannot explain the observed mass loss.

The radial pulsations of Miras have attracted a lot of attention in the discussions of mass loss from them because the radial pulsation is very conspicuous. Against the background of the radial pulsations high frequency sound waves have attracted little attention observationally. One may draw the analogy of a ship on the ocean in a storm. What one sees are the great waves tossing the ship up and down. In deep water sea waves involve no mass transport, so that the ship is not moved towards the shore and it is in no danger from the waves. The danger comes from the currents in the sea which are not noticeable by comparison with the waves, but slowly move the ship to the shore where it will founder. Radial pulsations are the great waves which are spectacular but cause no mass loss. The sound waves are the sea currents which in fact drive the mass loss.

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