MASS TRANSFER BETWEEN BINARY STARS

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The transfer of mass from one component of a binary system to its companion can involve ejection of the mass by radiation pressure, by Roche lobe overflow, by centrifugal action through the coupling of the upper atmosphere to the stellar rotation through magnetic fields, and by the dynamics of the atmospheric fluid under the action of an energy source at the photosphere or lower chromosphere. I will primarily address the latter mechanism, which commonly goes under the title of stellar winds. The major determinant of a stellar wind is the energy source. In the case of a binary system, the dynamic effects of the system on the flow pattern, particularly for close binaries, is a second major determinant, once an energy source is available to drive the wind.

In addition to ejection, the transfer of mass requires capture of the ejcted matter by the companion. The first issue is free particle *vs.* continuum flow. I will only consider continuum flow, as I doubt the applicability of the free particle concept to any binary system with significant mass transfer, because of the scale height and because of the likely presence of magnetic fields in the interstellar plasma. For more distant binaries, rather simple considerations show that the capture of matter for continuum flow can be enhanced over that for free particle flow.

Now for mass ejection through fluid dynamics. As shown by Parker years ago, a static stellar atmosphere is unstable, provided its temperature is high enough. The corona of the Sun, $T > 10^6$ K, flows outward in a continuous, though highly variable wind, as predicted by Parker and discovered by the Mariner 2 spacecraft. It seems clear from the work of Parker and others that any star with a hot corona will have a stellar wind.

The existence of the hot corona itself appeared paradoxical, since its energy presumably comes from the solar interior through the relatively cold photosphere and chromosphere. The spontaneous flow of heat from the cold photosphere to the hot corona directly violates the Second Law of Thermodynamics. The resolution of the paradox, of course, is that the energy does not flow as heat, but rather as mechanical energy that is

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dissipated into heat in the chromosphere and corona. In the solar corona only a fraction of the mechanical energy appears as heat - most shows up in the kinetic energy of bulk motion of the solar wind. The stagnation temperature of the relatively cold solar wind is ≅ 30×10^6 K.

For the Sun, the mechanical energy flow is in the form of acoustic waves generated by the deep convection zone. As the waves move outward their amplitude increases until dissipation occurs.

For single main sequence stars, acoustic waves from deep convection zones have had great success in explaining heating of the upper atmosphere. However, stellar winds can only be observed for the Sun, so that the accepted model, based on the systematic decrease in chromospheric emissions and increase in stellar rotation from late to early type stars is inferential.

In studying binaries we have a richer field. It is possible to observe the effects of winds, if they exist, as they impinge on companions. There are sources of disturbance in the lower atmosphere, other than acoustic noise associated with deep convection zones, that can drive stellar winds, for example, *g*-mode oscillations and X-ray heating. I conclude by describing some results of model calculations for binary systems showing how relatively small disturbances in the lower chromosphere or photosphere can cause substantial mass ejection in binary systems.

The model is a numerical integration of the equations of motion, including the energy equation, with an initial static atmosphere and with various temperature fluctuations imposed at the base of the corona. The initial static atmosphere is isothermal in the corona, with a linear temperature profile in the chromosphere. The flow is calculated along the line of centers between the two components, in the rotating frame of the system, so that the centrifugal force is included. The Coriolis force is not included, so that the present model is not valid for close binaries with large orbital angular velocities. Energy flows by convection, by thermal conduction, and by propagation of longitudinal pressure waves.

There are two *ad hoc* assumptions: The flow is one-dimensional in a diverging/converging flux tube configured to produce radial flow at each star, and dissipation of waves is included as a coefficient multiplied by the velocity gradient. The flux tube parameters can be adjusted to correspond to the capture cross-section, once that problem is solved.

The model has been applied to several situations: using a linear temperature pulse it has been shown that a substantial rise in the temperature at the base of the corona can account for the mass ejections needed to cause the X-ray turn-ons observed in HZ Her. It is hypothisized that *g*-mode oscillations may account for the temperature fluctuations through the amplitude amplification mechanism mentioned above. By starting the disturbance further down in the atmosphere, the model shows that rather small temperature fluctuations lead to large mass ejections.

An application that tends to validate the model is the quiet Sun. Beginning with a static chromosphere and corona, a periodic oscillation in the lower corona of about 10% of the static value initiates mass ejection that grows into a typical quiet-time solar wind in a few hours.

For sources of disturbance other than convection zones (say, X-ray heating), the altitude of the initiating disturbance may vary. This altitude is very important in determining the disturbance amplitude required for a given velocity of ejection, since for disturbances higher in the chromosphere, the amplification with outward propagation is reduced.

There is also a considerable effect of altitude on mass loss, both because of the amplification and because there is less mass in the atmosphere at high altitudes. For the HZ Her X-ray turn-ons, a disturbance at the base of the corona must be of the order of the coronal temperature in amplitude, whereas at lower altitude 10% disturbances will suffice.

The principal result of this work is that any modest disturbance at low altitudes can cause mass loss through a stellar wind mechanism, due to the amplification of the disturbance as it propagates into the thinner atmosphere. Binary stars offer a good application to such an approach, since it is possible to observe the effects of mass ejection. For a better model, the *ad hoc* assumptions of dissipation coefficients and flux tubes need replacing by careful analysis of decay mechanisms and the fluid dynamics capture problem.