

On the Disruption of a Protoplanetary Disk Nebula by a T Tauri Like Solar Wind

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Summary. The contrasting theoretical work by Horedt and by Elmegreen on the evolution of a disk nebula that surrounds a windy star are compared. The protoplanetary nebula will not readily be blown away by a centralized stellar wind; instead it will migrate toward the star, possibly ending up on the star, as a result of wind-driven turbulence and viscosity in the disk.

Key words: protoplanetary disk nebulae — T Tauri winds — protostars

I. Introduction

An important theoretical problem relating to the formation of the solar system concerns the manner in which the gaseous protoplanetary disk can be cleared away after the planets form. Cameron (1973) suggested that if the Sun had a T Tauri phase wind, then the pressure from this wind could somehow remove the nebula. There are now two theories of how this removal might actually occur. Their contrast is remarkable: Horedt (1978) and Elmegreen (1978) both assume the same model geometry and wind parameters, but Horedt (1978) concludes that the disk nebula will be blown away from the central star, and Elmegreen (1978) concludes that most of the nebula will migrate *toward* the central star. The purpose of the present paper is to compare these contradictory results.

II. The Model

The protostellar nebula may be adequately represented by a (non-self-gravitating) Keplerian disk with some specified radial distribution of column density. The central star is assumed to have a radially-directed, constant-velocity wind (before it interacts with the nebula). The wind velocity, v_w , is expected to be similar to that observed in T Tauri stars, namely, several hundred kilometers per second, and the kinetic power ($\dot{M}_w v_w^2/2$ for mass loss rate \dot{M}_w) may be taken to be some 1%–10% of the stellar photon luminosity, again in analogy to T Tauri stars. With such simple assumptions, the nature of the interaction between the wind and the nebula should be determinable from first principles.

III. The Interaction

We first consider the location of the wind–nebula interface. This interface will occur at some height above the midplane

which depends on the position in the nebula. Horedt assumes that this height will be such that the local nebular gas density will be so low that the mean free path of a wind particle will be comparable to the distance from the star. For his range of parameters, this is approximately where the density is $10^{-8.7}$ times its value in the midplane [a similar but more precise definition of his nebular height is in Eq. (5)]. Elmegreen derives the nebular height by assuming that the interface will occur where the normal component of the wind's pressure equals the local gas pressure in the nebula. In both cases, the wind–nebula interface is concave. The latter result is based on dynamical considerations; for example, the nebular gas pressure at the height proposed by Horedt is so low that the wind will clear away the gas there and penetrate deeper into the nebula. Thus the surface described by Horedt can only be transient; pressure balance will eventually be achieved, and the wind–nebula boundary will thereafter remain fixed on a dynamic timescale.

A second physical consideration is the manner in which the wind transmits its pressure to the nebula. Horedt assumes that both the energy and momentum of the wind are transferred to the nebular gas, the energy being partitioned between the enhanced nebular thermal energy, macroscopic motions of the nebular gas, and dissociation and ionization of molecules. On the other hand, Elmegreen considered only the transfer of the momentum in the wind to the nebular gas. The difference arises because at the wind–nebular interface used by Horedt, nebular matter may not be picked up by the wind at a fast enough rate to cause the wind to shock (Biermann et al., 1967). At the more likely pressure-balance interface however, the mean free paths are very low: the ionized wind particles will charge-exchange within a few meters of the nebular surface and the energetic neutrals will deposit their momentum within several tens to hundreds of meters from the surface. This results in a shock in the wind, as calculated by various authors for the analogous case at the interface between the present-day solar wind and a comet. The shock in the wind has important consequences, because it radiates away most of the wind's energy. Only $\sim 0.1\%$ of the energy flux in the wind goes into macroscopic motions in the nebula, which are continuously dissipated as turbulence. Thus the nebular gas cannot readily be removed from its gravitational potential well because most of the wind's energy is not available for such use.

This implies that the nebula cannot be dissipated by energetic processes like evaporation (since radiative cooling will

be effective) or direct energy exchange between the wind and the nebula; it must be the momentum carried by the wind, rather than the wind's energy, that leads to nebular evolution. In that case, the angular momentum of the disk must be conserved if the wind is radially directed, and this conservation makes it very difficult or impossible to move the nebular gas out to large radii. The importance of angular momentum has been emphasized by Handbury and Williams (1976) who suggested that a typical wind could not *push out* a typical nebula at all. Angular momentum carried by the wind could cause the disk to expand temporarily, but after the central star transfers most of its angular momentum to the nebula, this expansion will stop and the disk evolution discussed by Elmegreen will proceed.

The following interpretation of the wind-disk interaction considers all these points (see Elmegreen 1978 for details): (1) The wind pushes on the high altitude nebular gas and establishes an interface by pressure balance. (2) The wind moves nebular gas that is immediately below the interface away from the star for a short distance, by the conservation of its linear momentum. (3) This wind-induced motion will *mix* with underlying nebular material as a result of a Kelvin-Helmholtz instability (since there is a relative motion between two components of the same fluid and the Reynolds number is much too large to allow a laminar flow). Even if it did not mix, it would have a *maximum* excursion that results from angular momentum considerations: if the viscous forces between the outflowing gas and the underlying material in the nebula are large, then the outflow can go to a large distance before it reaches a new centrifugal force-wind-gravity equilibrium because it picks up angular momentum as it moves outward. If viscous forces are low, the wind induced outflow can go only a small distance. The actual mixing length determined by the Kelvin-Helmholtz instability will be comparable to the excursion in this latter case of low viscosity, so the mixing can occur without violating angular momentum conservation. We find that the mixing length will be roughly 2%-5% of the radial distance from the central star, depending on the various wind-nebular parameters. The relative velocity between the outflow and the underlying gas will be subsonic, both during the outflow (because sound waves will dissipate excess shear) and at the time of mixing (because even if the outflow conserves its specific angular momentum before it mixes, the differential orbital velocity over the mixing length is subsonic). (4) This constant mixing creates turbulence in the upper layers of the nebula. The source of energy for this turbulence (which dissipates rapidly) is the viscous force between the outflowing gas and the underlying nebula multiplied by the excursion length. The power available for turbulence exceeds the turbulent dissipation rate if $v_0\lambda/cx > 1$ for mixing length λ , orbital velocity v_0 , sound speed c , and distance to the star x . This is a necessary condition for the presence of fully developed turbulence (the Reynolds number is always very large), and it is satisfied over a wide radial range in most protoplanetary nebula models. (5) The wind-driven turbulence in the upper layers of the disk will enhance the viscosity enormously, so the velocity shear resulting from differential orbital motions will create viscous torques on the nebular matter. (6) The result of these viscous torques is that nebular matter will drift inward, as shown by Lynden-Bell and Pringle (1974). A small fraction of the total mass will carry the total angular

momentum outward. The torque will consist of two components: one results from the wind-induced mixing of nebular gas (since outbound parcels of gas will have different specific angular momenta than the underlying material with which they mix), and one results from viscosity-induced shear stresses. Each component of the torque contributes something to the total mass inflow. The mixing-induced torque produces a mass inflow which exactly equals the mass outflow produced directly by the wind. This is an obvious consequence of the conservation of angular momentum. Thus the wind-induced motions do not *directly* cause the nebula to redistribute its matter. Only the second source of torques, the shear stresses, cause the nebula to evolve. The net result is a slow (subsonic) inflow of matter along the top surface of the nebula.

The time scale for the nebula to evolve significantly was calculated for various wind-nebula parameters (Elmegreen, 1978). It may be approximated for a distance of 1 AU from the star by the expression

$$\tau = \frac{10^{12} \text{ s}}{3\zeta} \left\{ \frac{M_N/10^{-2} M_\odot}{x_{\text{max}}/50 \text{ AU}} \right\}^{1.37 \pm 0.21} \left\{ \frac{\dot{M}_w v_w}{2 \cdot 10^{26} \text{ dyn}} \right\}^{-1.33 \pm 0.15}$$

where M_N is the nebular mass contained in the distance x_{max} , and ζ is a dimensionless coefficient of viscosity, probably equal to around 0.1, and defined as the factor by which the product of the local turbulent length and the turbulent velocity must be multiplied to give the viscous stress coefficient.

IV. Conclusions

Some important consequences of such nebular evolution are: (1) If some inflowing nebular material can absorb stellar energy near the star (*not* from the wind, but from the *star*), and thereby turn around to join the wind, then a system with positive feedback can result, and there may be a runaway increase of the wind's strength. Presumably, the wind and the rate of nebular disruption will increase to a point of saturation, where the total momentum or energy flux in the wind becomes saturated to a value determined by the total luminosity of the star. This may explain the origin of T Tauri winds. (2) Much of the material in the wind itself may have come from the nebula (which may be only a small fraction of the total nebular mass). Thus a pre-mainsequence star may not lose mass during the T Tauri wind phase, it may in fact gain some (from the nebula), and the appearance of mass loss may be the result of a transfer of a small fraction of the mass in the nebula to the wind at some point near the star. (3) The structure and evolution of wind-disk systems were shown to provide a simple explanation for many of the perplexing details of protostellar H₂O masers (Elmegreen and Morris, 1979).

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