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Chromospheric Dust Formation, Stellar Masers and Mass Loss

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ABSTRACT

I outline a multi-step scenario which describes a plausible mass loss mechanism associated with red giant and related stars. The process involves triggering a condensation instability in an extended chromosphere, leading to the formation of cool, dense clouds which are conducive to the formation of molecules and dust grains. Once formed, the dust can be driven away from the star by radiation pressure. Consistency with various observed phenomena is discussed.

New View of Red Giant Chromospheres

The analysis of cool stars has benefited from reference to the Sun as a well studied archetype. However, in the past few years, it has been recognized that the solar analogy must be applied with caution, especially in the case of much lower surface gravity. Quantitative analyses of red giant chromospheres use ultraviolet lines of singly ionized carbon, to derive temperature (Brown and Carpenter 1984), densities and physical extent (Carpenter, Brown and Stencel 1985; cf. Hartmann and Avrett 1984).

These analyses combined with other multispectral studies indicate that red giants and supergiants altogether lack solar-like coronae, but instead fill comparable volumes with extended warm gas having densities of order 10E7-10E8/cm3 at temperatures of order 8,000 degrees Kelvin. Chromospheric radial dimensions are at least several stellar radii; approximately 10E14 cm for the supergiants. Maintenance of this extended warm region can be accomplished by absorption ionization of UV and EUV photons. In what follows, I argue that cooling can occur in two co-existing thermal regimes: chromospheric UV line emission in "warm" regions, and via molecular masers and thermal emission from dust in "cool" regions. This thermal bistability may contribute to the observed mass loss and other properties of such stars (cf. Goldberg, 1983).

Cooling via Condensation Instability

Key point: if you compress a chromospheric gas (8000K, 1E7/cm3), a condensation instability occurs because as the density rises, the radiative cooling increases with the density squared. Because this happens on the very steep portion of the radiative power loss curve (cooling rate, ergs/cm3/sec-vs-temperature, cf. Raymond et al. 1976), there is a dethermalizing runaway to very low temperatures.

An original application of this physics was described by Field et al. (1969) for the two-phase interstellar medium, where they derived "two thermally stable gas phases that coexist in pressure equilibrium, one at 10,000K and the other cooler than 300K." Their model was derived for interstellar gas heated by low energy cosmic rays. The resulting partition cooled 75% of the gas.

Lepp et al. (1984) have more recently confirmed this basic result for matter in the presence of radiation fields. By including high energy photons, they also derived an inverse Compton term and thus a coronal gas phase. Although a steady state solution, this model replicates the three-phase interstellar medium and makes predictions for quasar clouds. The coronal result does not apply to stellar chromospheres which lack a source of hard photons. The range of pressures and heating/cooling channels described by Lepp et al. imply applicability to the lower temperature physics of the putative two-phase chromospheres.

Instability Trigger Mechanisms

Basic stellar structure suggests that red giants possess large convective envelopes in response to steep temperature gradients Schwarzschild (1975). Convective motion provides a source of "acoustic noise" that will give rise to pressure perturbations in an overlying atmosphere. The density enhancement can trigger the condensation instability. To avoid shock waves which could produce high temperature emission lines, either the input energy varies slowly or the density profile with height is less steep than exponential. I prefer the latter, anticipating a quasi-isobaric extended chromosphere. Many cool, evolved stars pulsate. Shock phenomena may dominate those atmospheres, but it is possible that this scenario plays a role in regions where, or at times when, shocks are less important.

Formation of Molecules and Dust

The condensation instability yields conditions appropriate for the formation of molecules and grains. As a result of the rapid cooling and enhanced densities, molecules are formed in excited states and then cool via maser emission. Recent work by Elitzur and Cooke (1985) states that H_2O masers occur for densities at and above 1E9,cm3, are collisionally pumped and correspond to a 1000K excitation temperature. This is exactly the higher density, lower temperature condition expected from the condensation instability. VLBI studies show SiO masers occuring within a few stellar radii of dusty objects, like IRC+10216 (Lane, 1982; Johnston, et al. 1985). While the detailed chemistry is still to be elaborated (Kozasa et al. 1984; Maciel 1973, 1976), we may be seeing a manifestation of the condensation instability process.

Interferometric mapping of the 10 micron emission associated with silicate dust grains indicates a lack of such emission inside of approximately 10 stellar radii in many dusty objects (cf. Sutton et al. 1977). However, molecular clusters and less-annealed silicates with spectral features at other than 10 microns could be forming within this inner dust radius. SiO masers within 10 stellar radii are probably associated with this chemistry. Chromospheric and envelope expansion velocities require months - years for material to move several stellar radii. This places temporal constraints on cluster formation and subsequent dust nucleation (Donn and Nuth 1985). High spatial resolution observations of radial and azimuthal spectral variations may reveal the entire process.

Quenching Chromospheric Radiation/Accelerating Dust

Extended stellar chromospheres are optically thick to the usual radiative loss channels (hydrogen lines, Ca +, Mg +). The chromospheric gas is filled with photons of the Lyman series, scattered endlessly and effectively trapped (Wilson 1960). This radiation field could act on the newly condensed molecules and grains to provide acceleration and eventual expulsion. Jura (1984; 1985) has already concluded that once grains form near these stars, radiation pressure can accelerate them to infinity.

An extended chromosphere could trap part of the star's bolometric luminosity in endlessly scattered Lyman transitions. A 10E-7 Mo/yr mass loss at 10 km/sec requires an energy content which is comparable to less than 10E-4 of the bolometric luminosity. If we "quench" these chromospheric photons, transferring their energy to mass motion of grains, the net effect will be a lack of, or reduction of observed ultraviolet chromospheric emission, as discovered by Hagen, Carpenter and Stencel (1985). The radiative transfer applicable to this reduction of resonance line flux was discussed by Wehrse and Kalkofen (1985), where factors of five in flux reduction were derived. In light of the detection of UV chromospheric emission from dusty stars, this scenario provides an alternative to the quenched chromosphere idea of Jennings and Dyck (1972), which was based on the lack of Ca II emission in dusty stars.

Further Work

To further investigate the validity of this scenario, several lines of work are required. First, the timescale for the growth of the instability needs to be evaluated, against the constraint of the "fully formed" 10 micron silicate dust emission features outside of ten stellar radii. Second, an observational test involving high spatial resolution spectral imaging is needed to monitor radial and azimuthal changes in the infrared dust emission profiles, in response to nucleation, growth and processing of dust grains in the circumstellar environment. Finally, the role of this process in the atmospheres of cool, pulsating stars deserves study. I am happy to acknowledge useful discussions with Joseph Nuth and Leo Goldberg in the preparation of this report.

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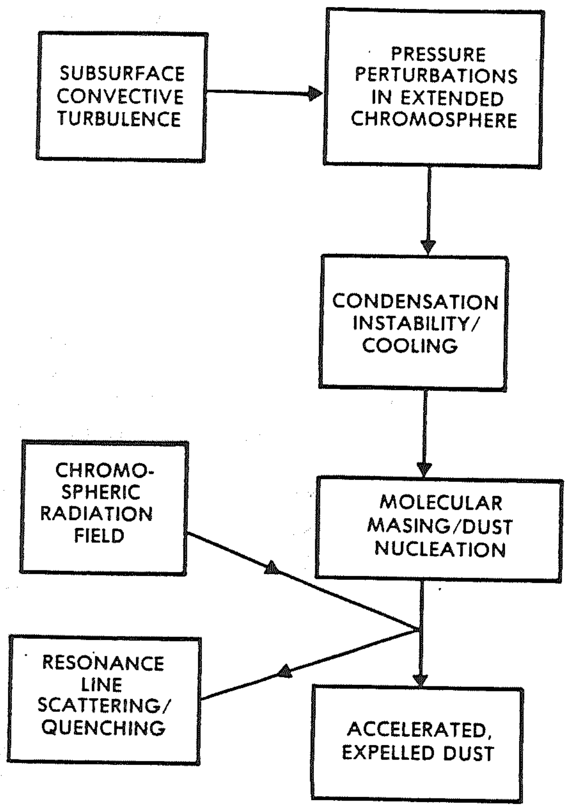
Mass Loss Scenario



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