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A new paradigm for stellar evolution including detailed mass loss processes

ABSTRACT

We present a new paradigm for stellar evolution which deals with a detailed treatment of mass loss processes. The paradigm is presented as a logical diagram which describes the respective dependencies of atmospheric properties relevant to mass loss generation.

INTRODUCTION

"Classic" paradigms of stellar evolution describe the changes of the evolutionary status of stars by modeling the dominant nucleosynthesis processes in the stellar cores. Mass loss, which plays a crucial role for the "right" choice of the stellar evolution tracks, is therein considered as a given function of the position of the star in the H-R diagram. We note that this scenario is somewhat incomplete because the evolution of stars in turn generates specific conditions, which allow the mass loss rates to be explained in physical terms. Atmospheric conditions relevant to the generation of mass loss include global oscillations, convective instabilities, changes in the thermal pressure scale height, thermal bifurcation, and formation of molecules and dust. In general we have to consider the principal effects of interior evolution on stellar atmospheres, including consequences of these effects on mass loss as well as consequences of mass loss on stellar evolution. In our discussion we limit our consideration to that range of stellar masses and ages when convective envelopes are present.

PRINCIPAL EFFECTS OF INTERIOR EVOLUTION

The effects of interior evolution on stellar atmospheres are caused by changes of the internal energy generation rate. The net effect of gradual exhaustion of a given, current core fuel is a resulting increase in central temperature and corresponding eventual increase in stellar luminosity. For solar composition, the envelope and atmosphere response includes an overall increase in radius and reduced surface temperature and gravity. This change affects the generation and transmission of short and long-period wave modes and promotes atmospheric conditions for thermochemical instabilities and thermal bifurcation.

Stars undergoing *shell burning* exhibit this set of changes on a relatively shorte timescale, especially when the shell is approaching the core/envelope boundary and/or is undergoing transient *flash events*. Those stars initiating *core burning* change their interior structure in an opposite manner, leading to reduced radius, higher surface temperature and gravity boundary conditions not as conducive to thermochemical instabilities. Doom et al. (1986) and Maeder & Meynet (1989) have studied in detail the evolution of stars with different masses.

CONSEQUENCES OF THESE EFFECTS ON MASS LOSS

We consider four observable stellar properties (emergent stellar radiation, subsurface convective turbulence, global oscillations, and magnetic fields) which are certain consequences of stellar evolution.

Emergent stellar radiation plays a crucial role in the production of mass loss in evolved stars. Radiation forces act on molecular lines (e.g., Maciel 1976, 1977, Elitsur et al. 1989) and on dust grains (e.g., Kwok 1975). Reduction of the stellar effective temperature promotes conditions for the formation of molecules, which in combination with hydrodynamic enhancement of atmospheric density, provides an abundance of extra opacity to capture photon momentum. Thermal bifurcation which becomes very effective in evolved giants and supergiants depends crucially on the stellar radiation field (Ayres 1981, Kneer 1983, Muchmore 1986, Muchmore et al. 1987). These and subsequent points are diagrammed in Fig. 1.

Subsurface convective turbulence cannot directly control the mass loss behavior of a star. However, it seems to be essential for significant mass loss to occur, because it generates short-period acoustic waves which propagate outward to higher atmospheric layers and lead to the generation of stochastic shocks (e.g., Cuntz 1987). These shocks account for heating to chromospheric temperatures, which cool by emission of UV radiation. Cool molecular material so irradiated may form molecular ions which serve to catalyse molecular reactions, including those leading to the formation of molecular clusters and dust particles (e.g., Gail & Sedlmayr 1986, Mamon et al. 1987). However, it is surely a different mechanism which places sufficient amounts of mass in the upper stellar atmosphere to begin with (e.g., Cuntz 1990).

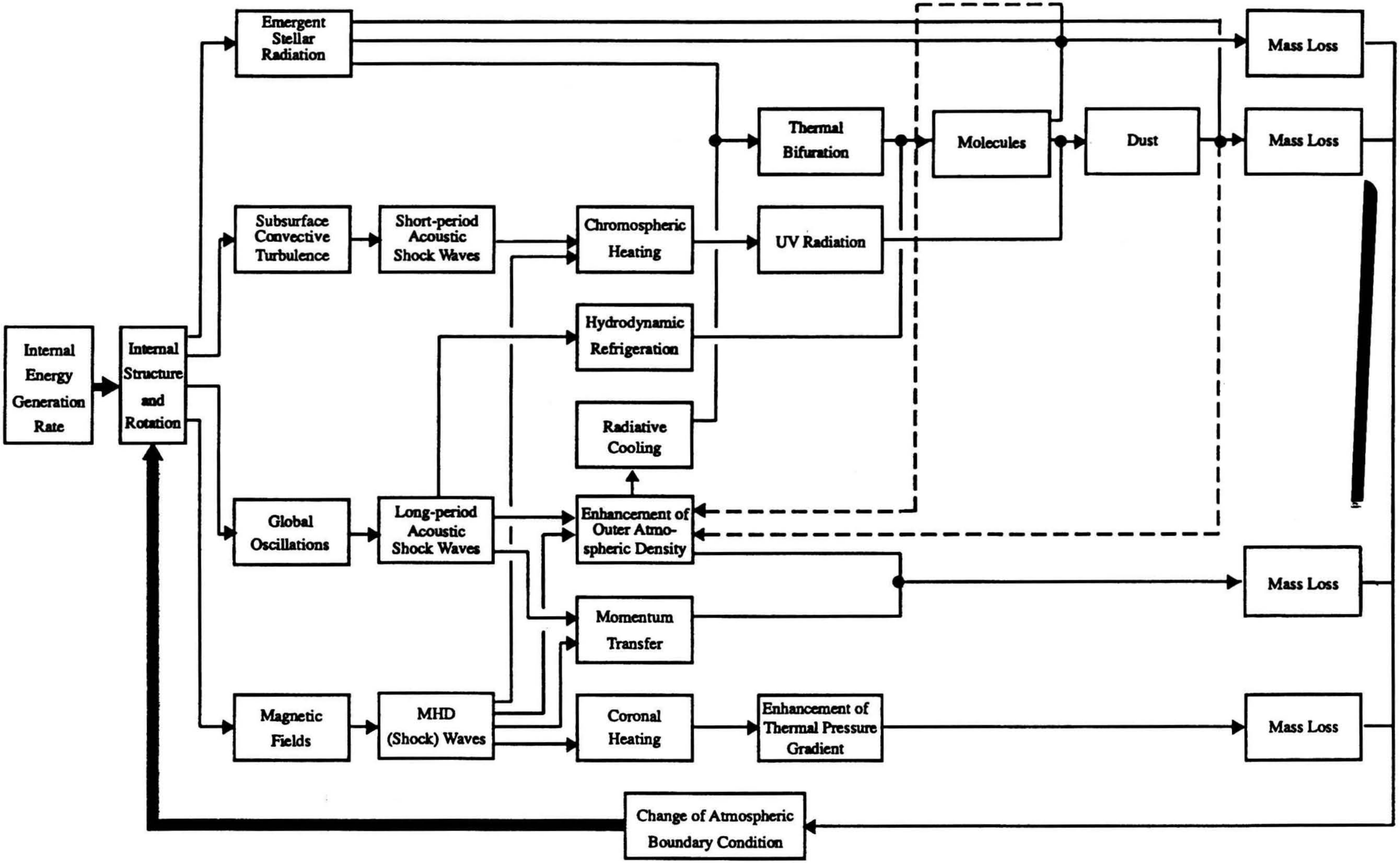

Fig. 1: The new Paradigm of Stellar Evolution

Global oscillations are a direct consequence of interior structure and are most sensitive to (and changeable by) the evolution of the internal energy generation rate. The influence of global oscillations on the stellar atmosphere is threefold: First, they lead to a substantial enhancement of the outer atmospheric density. Second, global oscillations can promote atmospheric dynamics due to momentum transfer. The combined influence of both effects can lead to mass loss, depending on the particulars (e.g., Wood 1979, Bowen 1988). In addition, global oscillations can, third, produce hydrodynamic refrigeration, when radiative cooling and hydrodynamic interaction in time–dependent atmospheric flows reduce outer atmospheric temperatures to below radiative equilibrium values. The onset of thermochemical instabilities can subsequently lead to the formation of molecules and dust. A paradigm for dust–driven mass loss based on observational constraints was already supplied by Stencel et al. (1986).

Magnetic fields serve largely to limit mass loss while the interior dynamo is effective enough to produce closed loop geometry, leading to coronal heating, which cannot otherwise be provided by acoustic shock wave dissipation (e.g., Stępień & Ulmschneider 1989). Hot coronae provide a drastic increase in the thermal pressure gradient, leading to Parker–type stellar winds with high speeds but very low mass flux (Parker 1958, Hammer 1982, among others). However, late–type giant and supergiant stars largely lack coronae, suggesting reduced significance of the dynamo. It is suspected that these stars may lose mass due to dissipation of Alfvén waves along mostly open magnetic field geometries (e.g., Hartmann & MacGregor 1980), although this mechanism is uncertain because the required magnetic fields are undetectable in most of these stars (e.g., Marcy & Bruning 1984).

CONSEQUENCES OF MASS LOSS ON STELLAR EVOLUTION

Fundamentally, there are two limits in which stellar mass loss could affect internal structure and possibly evolution. First, when the dynamo is effective, magnetic braking can slow the stellar rotation over a main sequence life time, as is strongly suggested by the observed correlations of X–ray flux with rotation rates (e.g., Rutten 1987). Second, when the mass loss rate grows large with respect to the total stellar mass and the nuclear timescale of internal energy generation, the entire envelope (in extreme cases) could be removed before a shift in nuclear fuels or a shift from core to shell burning (or subsequent core re-ignition) has a chance to occur. Our contention is that less extreme internal changes can cause or be affected by the onset of heavy mass loss due to stellar pulsation and dust formation epochs. The generation of extensive circumstellar shells around red supergiant stars (Stencel et al. 1989) may be an example of this behavior. Quantification of the paradigm outlined here should permit us to eventually compute improved boundary conditions to be incorporated into detailed stellar evolution models.

ACKNOWLEDGEMENTS

We are pleased to acknowledge support for this work through NASA grants NAG 5-1374, NAG 5-816, and NAG 5-1214 to the University of Colorado and (M.C.) through the DFG grant Cu 19/1-2.

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