Molecular Cooling in the Outer Atmospheres of Red Giants

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In the outer atmospheres of cool giants and supergiants there is a competition between heating by shock waves which develop from noise lower down in the convection zone and radiative cooling. The post-shock cooling is most effective in keeping temperatures low and in damping shocks if molecules (especially CO) form. CO is important both because of its high dissociation energy (11 eV) and its large IR opacity.

If it is in LTE, CO can quickly cool atmospheric gases to $T \leq 1000$ K, permitting dust formation quite near a star's photosphere. However, in low density gas which is regularly shocked, chemical reactions may be too slow to keep molecular abundances in equilibrium at the momentary temperature.

Upper and lower bounds for plausible molecular formation rates for CO behind shocks are $d \ln N_{\mathrm{CO}} / dt = k N_{\mathrm{O}}$, where N represents particle density and k is a reaction rate constant with a value of 10^{-11} to 10^{-17}. For conditions appropriate for the region identified in empirical studies as the temperature minimum in Arcturus (K2 III), we find that the time scale for molecule formation is likely to be roughly (*very* roughly considering the broad range of plausible reaction rates) comparable with the time scales for shock repetition, which are a few hours for weak shocks and 1–2 days for stronger shocks (Cuntz and Muchmore, 1989).

Approximate solutions for the behavior of post shock temperatures show that CO is an effective coolant when the time scale for molecular formation is no more than about 10 times longer than the period between shocks.

Most significantly, we conclude that molecular abundances in the outer atmospheres of red giants will generally be out of equilibrium, lagging in time behind temperature and density fluctuations. At lower densities — farther from a star or in stars with lower g, i.e. the conditions expected in the majority of giant atmospheres — molecules would not have time to associate at all between shock heating events.

Cuntz, M. and Muchmore, D., 1988, *Astr. Ap.*, submitted

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