

CONSTRAINTS ON NEBULAR DYNAMICS BASED ON OBSERVATIONS OF ANNEALED MAGNESIUM SILICATE GRAINS IN COMETS AND IN DISKS AROUND HERBIG Ae AND Be STARS.

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Introduction: “Crystalline” olivine grains were first observed in the infrared spectra of dust surrounding Comet Halley[1] and have since been observed as a component in the dust of several other comets[2], including Comet Hale-Bopp[3]. In addition, infrared observations of the disk surrounding Beta Pictoris[4] indicate the presence of crystalline olivine. More recent infrared observations of the spectral evolution of the disks of pre-main-sequence A and B stars show the gradual development of crystalline olivine[5] from dust originally resembling typical “astronomical silicate”[6], the silicate dust component of the interstellar grain population. (Astronomical silicate is the primary model for amorphous silicate dust used to interpret everything from the spectra surrounding mass-losing red giants to the emission spectra of embedded protostars, but does not really correspond to the spectrum of any known rock or mineral. Interpretation of the development of crystalline olivine grains from such starting materials is therefore enigmatic.)

Hallenbeck et al.[7] recently completed a study of the annealing of initially amorphous magnesium silicate smokes as a function of time and temperature. This study demonstrated that spectra resembling those identified as “crystalline” olivine can be produced from amorphous magnesium silicate smokes by annealing at temperatures on the order of 1000K within a month, and at temperatures near 1100K within a few seconds. Annealing at much lower temperatures required considerably longer to achieve the same result: more than 5,000 years at 925K, in excess of 30 million years at 875K. Preliminary studies of the annealing of initially amorphous iron silicate smokes indicate that these grains anneal even more slowly than do magnesium silicates and require temperatures well in excess of 1200K to achieve any degree of detectable change in their IR spectra on timescales of days-to-weeks.

Implications for Cometary Grains: Average silicate grains in the interstellar medium or in dense molecular clouds are amorphous and well represented by “astronomical silicate”[6]. In order to convert such grains – or a subset of this population – into grains resembling “crystalline olivine” requires exposure to temperatures as high as about 1100K for a few sec-

onds or as low as 900K for millenia. It might be possible to achieve temperatures on the order of 1100K for a few seconds as grains fall through the accretion shock and onto the protosolar disk[8]. However, if this occurs as a routine consequence of the accretion process, then the infrared spectra of all protostellar systems should resemble crystalline olivine. Alternatively, cometary grains might be processed through hotter, giant-planet subnebulae in the outer solar system. Unfortunately, the temperatures of the outer regions of these subnebulae – where grains are more likely to escape - are much cooler than 900K. Disruption of subnebulae to expose the hotter core regions would seem to be a rare event, at best.

Evidence from Herbig Ae/Be Stars: Only young A- and B- stars have sufficient luminosity in the ultraviolet to be easily observed just as they begin to break out of their natal cocoon. Studies of such systems have been carried out using both IUE and the Hubble Space Telescope[9] that have revealed direct evidence of infalling cometsimals at all evolutionary stages – from the youngest systems detectable in the ultraviolet to stars that are almost on the Main Sequence. Similarly, it has long been argued that the dust in stars such as Beta Pictoris must be replenished from infalling cometsimals or from other small bodies orbiting the star. This is based on calculations showing that small dust grains would be lost from the system due to radiation pressure on much shorter timescales than the 10-million-year age of this star.

As noted in the Introduction, observations of the infrared spectra of Herbig Ae and Be stars as a function of age reveal a steady evolution from “astronomical silicate”, indicative of relatively unprocessed interstellar materials, to “crystalline” olivine. The progression has been observed for stars just becoming observable in the ultraviolet to stars just getting to the Main Sequence (e.g. Beta Pictoris at ~ 10 million years). Stars of similar age have infrared spectra that look quite similar, thus indicating that this evolutionary sequence is a general phenomenon rather than a rare occurrence – such as the disruption of a planetary subnebula that might release processed silicates. In a similar vein, the earliest released dust shows no evidence for “crystalline olivine”, thus eliminating the accretion shock as the source of processed silicate.

Dust released in the oldest systems – and by comets in our own solar system – contains a considerable quantity of processed silicate, yet current nebular models do not appear to be able to account for the necessary level of processing required to produce such grains.

Dynamic Implications: The evidence above appears to indicate that comets formed continuously in the outer regions of the protoplanetary nebula and that the grains incorporated into those comets contained an increasing proportion of silicate dust processed at temperatures on the order of 1000K. The most logical place to achieve such sustained high temperatures in the solar nebula is near the terrestrial planet formation region. However, the monotonic increase in the proportion of processed silicate in the cometary population surrounding Herbig Ae/Be stars implies that there must be a steady circulation from the innermost to the outermost regions of such systems in order to carry processed silicates beyond the “snow line.” It is unlikely that this circulation could be due to the relatively small scale transport inherent in turbulent convective cells[10]. It seems much more likely that such transport would be accomplished in a steady flow above and below the nebular midplane as has been previously suggested by Prinn[11] and Stevenson[12].

Chemical Implications: If there is a steady flow from the inner to the outer regions of protoplanetary nebulae, the chemistry of the gas-phase would be dominated by chemical kinetics to a much larger degree than now envisioned [e.g. 13, 14]. In particular, such circulation patterns could lead to the continuous introduction of freshly condensed and partially annealed grains (relatively ideal natural catalytic surfaces) into the outer solar system. This could greatly enhance gas-grain reactions such as the Fischer-Tropsch conversion of carbon monoxide and hydrogen to hydrocarbons or the analogous conversion of molecular nitrogen and hydrogen to ammonia[15, 16].

It is interesting to note that no current model of cometary chemistry can explain the observed abundances of gas-phase material in cometary comae without invoking some degree of mixing between materials produced in warm, high-pressure, planetary sub-

nebulae and in the colder nebula itself. Little has been said concerning the probability of material within these higher-temperature, higher-pressure regions escaping from the subnebula to mix with surrounding gas. The introduction of a steady backflow from the inner, higher pressure and temperature regions of the nebula, to the cooler, cometary-forming, outer nebula could provide a sufficient quantity of reduced species such as ammonia and various hydrocarbons that planetary subnebulae might become unnecessary to understanding cometary chemistry.

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