PROCESSING OF CHONDRITIC AND PLANETARY MATERIALS IN SHOCKS ASSOCIATED WITH SPIRAL DENSITY WAVES IN THE SOLAR NEBULA: John A. Wood, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138, USA

Abstract of the abstract. An energetic nebular setting or environment has long been sought in which the material now in the planets and the chondritic meteorites was thermally processed. This paper proposes that the setting can be found behind shock fronts that accompanied the motion of spiral density waves through the solar nebula during the infall stage of nebular evolution. The substance of the nebula passed through these shock fronts many times, and each time there were opportunities for heating, melting, vaporization, chemical fractionation, and concentration of condensed matter between turbulent vortices. Only a small fraction of the potential planetary matter in the system, by responding to these opportunities, joined planetesimals and avoided being drawn into the sun.

The sun was formed by the self-gravitational collapse of a large volume of interstellar gas and dust. Because interstellar material has nonzero angular momentum most of it was not able to fall directly onto the protosun, but instead joined a disk of gas and dust orbiting the protosun. Material probably accumulated there, because in a symmetric disk no efficient mechanical process is known that would transfer angular momentum to the outer edge of the disk and allow the rest of the disk material to move in and join the sun. The nebula could grow in this way to approximately one-third the mass of the protosun. Above this critical mass the disk would have become gravitationally unstable and axially unsymmetric. It is currently thought that the disk would respond to gravitational instability by forming a non-axisymmetric pattern of spiral arms [1-3], somewhat analogous to those in galaxies.

Gravitational torques in such a non-axisymmetric nebula would be capable of redistributing angular momentum very efficiently. This may be what allowed most of the mass of the solar nebula to flow into the sun, while a smaller fraction of it, which received most of the disk’s angular momentum, was spun out to large radial distances. The flow of material into the protosun may have prevented the nebula from growing larger than ~0.3 its mass. Above this critical mass the disk would have become gravitationally unstable and axially unsymmetric. It is currently thought that the disk would respond to gravitational instability by forming a non-axisymmetric pattern of spiral arms [1-3], somewhat analogous to those in galaxies.

The corotation distance at which the angular velocities of disk material and the arm were the same. Inside the corotation distance disk material overtook the density wave; outside this critical distance the density wave overtook disk material. It is not known where the corotation distance might have been in the solar nebula. Figure 2 summarizes velocity differences in such a situation. Here the arbitrary assumption has been made that corotation occurred at the radial distance where Uranus now orbits. In the system postulated the velocity with which nebular material entered density waves at 3 AU, the approximate radial distance where the chondritic meteorites formed, was about 10 km/sec. This is a supersonic velocity, approximately mach 6 in the nebular gas. (Of course this value is directly dependent upon the assumption made about the corotation radius in the nebula.)

Thus in this model nebular material at ~3 AU passed through a standing shock front as it entered each spiral arm. In passing through shock fronts the nebular material was heated. The gas was heated by compression, and dust grains were heated by friction as they dragged against the decelerated gas. [4,5] have shown that solid particles can be strongly heated, even melted and vaporized, in such shocks (mach 6). This is a promising mechanism for melting the substance of chondrules, and for vaporizing planetary material as a preliminary to volatility fractionation during condensation. The concentration of preplanetary dust into chondrule precursors and, ultimately, planetesimals in such a mechanically violent environment is a nontrivial problem. An interesting possibility is that gas turbulence caused solid particles to concentrate. Each whirling vortex in a turbulent
gas has a tendency to spin solid particles out of it, like a centrifuge. [6] have shown in some preliminary computer modelling studies that the solid particles tend to accumulate and may be concentrated to a high degree in the stagnation zones between vortices.

During each passage of nebular material through a shock front inside the corotation distance, it was decelerated. Part of its angular momentum was transferred to the aggregate of material in the density wave, where it was in a position to be fed by gravitational torque to nebular material at greater radial distances. The decelerated material behind the shock front had a diminished orbital mean distance. As the material moved through the density wave and back into the disk at large it was reaccelerated, but (since the process was dissipative) it never regained all its preshock orbital energy and angular momentum. Thus nebular gas and entrained solid particles, in a series of passages through density waves, migrated inward to the sun.

It is likely that the mechanisms of thermal processing and turbulent concentration outlined above were inefficient, and during each encounter with a shock front only a small fraction of the dust in the system was converted to chondrules. Similarly, only a small fraction of the chondrules and dust in the system was aggregated into chondritic material. The production of chondritic (preplanetary) material at a given radial distance in the nebula can be seen as a quasi-steady-state process, wherein a small fraction of the solid material making its way to the sun is withdrawn from the stream during each encounter with a density wave, and added to aggregations large enough to pursue stable orbits and not be moved with the gas flow farther toward the sun.

There are many opportunities for chemical fractionation in such a complex process. As a single example, grains or chondrules that are rich in metallic FeNi, being substantially denser than siliceous objects of similar size, would be treated differently than the siliceous objects by the turbulent concentration mechanism of [6], forming aggregations that are enriched in Fe and Ni.


Fig. 1. Two modes of rotation in a protoplanetary disk (schematic). Arrow lengths are proportional to velocity. At some radial distance in the disk the two velocities are equal, and there is no movement of the density waves relative to the substance of the disk.

Fig. 2. Differences in velocity between disk material and density waves, as a function of radial distance, on the assumption that corotation occurred at the present radial distance of Uranus. The negative differential velocity shown outside Uranus means density waves were overtaking the substance of the nebula, instead of vice versa.