PRELIMINARY RESULTS ON FORMATION OF JETSTREAMS BY GRAVITATIONAL SCATTERING

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Alfvén and Arrhenius (1970) have considered the development and stability of jetstreams by collisional interactions among grains; and they propose that in a jetstream environment, grains may collect and adhere to form self-gravitating embryos. Gravitational attraction of smaller particles by these embryos may then lead to a net accretion because high relative approach speeds, which could erode or break up embryos, have been minimized during the formation of the jetstream.

As an embryo grows, the synodic orbital frequencies between it and the particles it attracts become greater than the collision frequencies among these particles and between these particles and the rest of the jetstream. At this point, the embryo rather than the primordial jetstream will determine both the orbital parameters a, e, and i that the particles near the embryo adopt and the distribution of the particles among these orbits. The question is, will the redistribution of particle orbits by embryos remove particles from the jetstream?

Figure 1 illustrates schematically how streams of particles are attracted to impact an embryo in a two-dimensional model developed by Giuli (1968*a,b*). Calculations for a three-dimensional model have been made, and they qualitatively support the results for the two-dimensional model. The dotted lines represent elliptical particle orbits as seen in a rotating coordinate system centered on a massless embryo. The coordinates rotate with the same period as the embryo's orbital period. As mass is added to the embryo, it attracts some of the particles of given a and e to impact, and it gravitationally scatters other particles from their former (a, e) orbits and places them in different (a', e') ones. The impact cross section of the embryo is greatest for those orbits that provide impacting particles with impact speeds v_i at or near the embryo escape speed v_e. There is a well-defined relation between a and e for impacting orbits with v_i/v_e = const = 1, say, such that, if the dotted lines in figure 1 represent (a_{max}, e_{max}) for these orbits, then all impacting orbits with $v_i = v_e$ are contained within the two regions defined by the inner and outer extremes of the dotted lines.

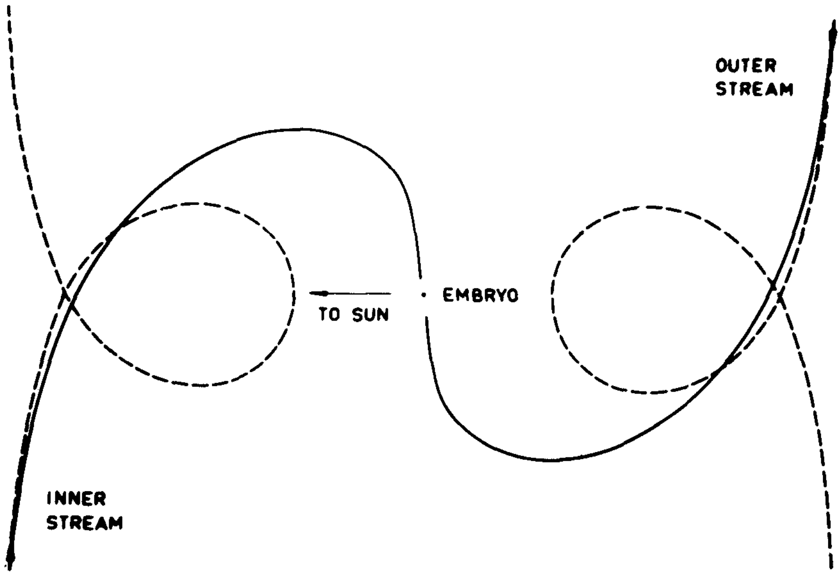

Figure 1.–Schematic illustration of particle streams gravitationally attracted to an embryo in the two-dimensional model developed by Giuli (1968*a,b*).

Calculations show that particles on impacting orbits with given v_i/v_e that do not impact on a given "pass" by the embryo will be scattered back into orbits with different (a', e') that are also impacting orbits with the same value of v_i/v_e, or else will be scattered into orbits with greater (a'', e'') that will eventually become impacting orbits with the same v_i/v_e as soon as the embryo becomes massive enough to reach them. In other words, if a particle is ever on an impacting orbit with given v_i/v_e, it remains on *some* orbit with the *same* v_i/v_e until it impacts, no matter how many times it is scattered before impact occurs. Spatially this means that, as the embryo grows, the particles that it does not capture on a given pass are shoved outward into more distant locations in the primordial jetstream, where they may be captured on succeeding passes. In two dimensions, the two "scattering jetstreams" (denoted by the inner and outer extremes of the two dotted lines in fig. 1) recede into the surrounding "viscous jetstream." The region between the scattering jetstreams is mostly devoid of particles; the regions outside are populated by the primordial jetstream particles; and the regions in the scattering jetstreams contain both primordial particles and particles relocated from the inner regions. Therefore, we expect the scattering jetstreams to have higher particle density than the viscous jetstream. In three dimensions, we expect the scattering jetstream to be a toroidal annulus of enhanced particle density, enclosing a tube of diminished particle density. In the center of the tube is the embryo.

Thus we see that the traditional (two-body) concept of an embryo growing by sweeping out a tube of matter of ever-increasing cross section is actually a valid concept, although the mechanics are rather involved.

Because the scattering jetstream is itself stable (particles are either stored or captured), the presence of embryos in primordial jetstreams does not destroy their stability.

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DISCUSSION

DOHNANYI: Have you had a chance to consider the influence on your accretion rates of competing processes; e.g., planetary perturbations, the Poynting-Robertson effect, and lifetime due to collisional breakup or erosion?

GIULI: No. We do not consider accretion rates in this model. To do that would require an estimate of the particle density during planet formation. That consideration will be an elaboration to the model.

SINGER: Is there a simple dimensional argument that can be put forth to explain the qualitative nature of the results for the gravitational accretion theory?

GIULI: Because the numerical integrations do display the asymptotic development of rotation with mass so dramatically, I feel strongly that there should be a simple explanation. As yet I have not found it.

ALFVÉN: One can show that if accretion occurs for any size body for which the total angular momentum contributed by the accreted material is some constant fraction of the angular momentum contributed by a particle that grazes the body tangentially with the body's escape speed, then the rotation speed acquired by the body is proportional to the square root of the body's density. Giuli's calculations show that the asymmetry of the impacts give about 1 percent of the tangential angular momentum for all masses.

WHIPPLE: It seems to me we are putting too much emphasis on the assumption that the process of formation of bodies produces a particular rotation rate. The limitation on rotation rates is density, not mass, and the solid bodies of the solar system have a small range of densities. The reason the observed rotation rates appear to cluster around certain values is that accumulation processes tend to give rapid rotation rates. Those bodies that tried to form with much higher rotation rates were disrupted and are not observed. Some bodies that were formed with lower rotation rates are observed. Forces that change rotation rates thus may destroy the bodies or reduce rotation rates, leading to the observed distribution.

GIULI: Getting back to Singer's question, and elaborating somewhat on Alfvén's comment: The rotational angular momentum per unit mass (specific angular momentum) contributed by an impacting particle that grazes a body with the body's escape speed (or with some factor of the escape speed) is easily shown to vary as the two-thirds power of the mass of the body, for a given body density. If any accretion process adds matter to an embryo in such a way that the sum of the contributions of specific angular momentum of added matter is some constant C times the two-thirds power of the embryo mass, then it is easy to show analytically that the asymptotic development of rotation rate with mass is an inevitable result, along with the period-density relation stated above by Alfvén. These points are developed by Giuli (1968*a*, *b*). The gravitational accretion calculations provide this relation between contributed angular momentum and embryo mass, for any particular body that grows with constant mean density, at any distance from the Sun. This fact is true over at least the seven orders of magnitude of mass for which I did the calculations. This is a result of the fact that the geometry of the impacting particle trajectories scales linearly with the radius of the body. I have no simple explanation of why this should be the case, but probably it is connected with the fact that all embryo masses for which I did the calculations were small compared to the solar mass. (The largest embryo mass considered was Jupiter's mass.) I should mention that one failure of the current model is that it gives a different value of *C* for the different bodies of the solar system. Fish (1967) and Hartmann and Larson (1967) have shown that most of the bodies of the solar system have the same value of *C* over a mass range of 11 orders of magnitude.

UREY: MacDonald was the first to consider the relation between specific angular momentum and mass, and he obtained a power of 0.83 rather than two-thirds. This came about because he included Mars. The value two-thirds applies only if all terrestrial planets are excluded. Is this justifiable?

GIULI: Mercury, Venus, and Earth are excluded because of the apparent tidal effects upon their rotation rates subsequent to their formation. Mars is a very serious problem. If no subsequent process has affected Mars' rotation rate, and if Mars and the other bodies have formed by the same process, then the validity of the present gravitational accretion model as representing the process of formation may be in doubt. On the other hand, the present model can explain a retrograde rotation for, e.g., Venus if some peculiar condition restricted the eccentricity of heliocentric particle orbits in Venus' vicinity to low values during its growth.

HAPKE: The final rotation state of the body after accretion is strongly influenced by the initial density distribution in the nebula. This follows from consideration of the conservation of angular momentum and is independent of the details of the accretion process. Consider small particles in orbit about the proto-Sun that later condense into a larger body. The material initially inside the final orbit will have been moved outward during accretion and the material outside will have moved inward. The orbital angular momenta of both sets of particles will have changed in opposite senses. In general, the net change will not be zero, and thus the orbital angular momentum difference will show up as the spin angular momentum of the body. The direction and amplitude of the rotation depends on the original density distribution and final orbit.

GIULI: Perhaps. I am currently investigating the question of whether an embryo captures particles from their primordial heliocentric orbits or redistributes them before capture. The current investigation suggests that the latter situation applies to most of the captured particles. Also, the work of Trulsen[1] suggests that an intermediate particle state may occur before embryo formation; namely, a viscous jetstream that modifies the primordial particle distribution over the distances of interest.

DISCUSSION REFERENCES

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[1]See p. 327.