The Early Solar System and the Rotation of the Sun [and Discussion]

T. Gold, H. Zinnecker, W. H. McCrea, R. J. Tayler, M. M. Woolfson and D. O. Gough

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The early Solar System and the rotation of the Sun

By T. Gold, F.R.S.

Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853, *U.S.A.*

In most discussions of the formation of the Solar System, the early Sun is assumed to have possessed the bulk of the angular momentum of the system, and a closely surrounding disc of gas was spun out, which, through magnetic coupling, acquired a progressively larger proportion of the total angular momentum. There are difficulties with this model in accounting for the inclined axis of the Sun, the magnitude of the magnetic coupling required, and the nucleogenetic variations recently observed in the Solar System. Another possibility exists, namely that of a slowly contracting disc of interstellar material, leading to the formation of both a central star and a protoplanetary disc. In this model one can better account for the tilt of the Sun's axis and the lack of mixing necessary to account for the nucleogenetic evidence. The low angular momentum of the Sun and of other low mass stars is then seen as resulting from a slow build-up as a degenerate dwarf, acquiring orbital material at a low specific angular momentum. When the internal temperature reaches the threshold for hydrogen burning, the star expands to the Main Sequence and is now a slow rotator. More massive stars would spin quickly because they had to acquire orbiting material after the expansion, and therefore at a high specific angular momentum.

A process of gradual inward spiralling may also allow materials derived from different sources to accumulate into solid bodies, and be placed on a great variety of orbits in the outer reaches of the system, setting up the cometary cloud of uneven nucleogenetic composition.

The angular momentum of the planetary system – the nine known planets – around the centre of mass of the Solar System, has a value of approximately 3×10^{43} kg m^2 s^{-1}. The angular momentum of the Sun, if it is assumed to spin internally with the period possessed at the surface at 16° latitude, is approximately 1.7×10^{41} kg m^2 s^{-1}. The Sun, possessing almost a thousand times as much mass as the planets, thus has only $\frac{1}{180}$ of the angular momentum of the system. This extremely uneven distribution of the angular momentum is of course a central issue in the discussion of the origin of the Solar System.

Uranus and Neptune have a mean density which suggests that they are composed chiefly of the light elements carbon, nitrogen and oxygen, and that they do not have much hydrogen and helium. If one considers that they formed from the condensation of these light elements out of a solar mix in the region of their present orbits, then this would imply that a very much larger quantity of hydrogen and helium once existed in that region and hence was endowed with the appropriate amount of angular momentum. This would increase the angular momentum possessed by the early Solar System, before the loss of this hydrogen and helium, by some very large factor, which could be as large as several hundred. In the early Solar System the Sun would then have possessed less than 1/10000 of the total angular momentum. In the formation process there must have been either an extremely efficient mechanism for distributing the angular momentum in this uneven way, or an extremely efficient selection of material from an original cloud, according to the angular momentum possessed.

The orientation of the angular momentum vector of the planetary system to the axis of the Sun is about $7\frac{1}{4}°$. Again, this relationship has to be accountable in a theory of origin. It is an interesting angle, for it is sufficiently small to imply a relationship in the setting-up process, and sufficiently large to imply that this relationship was not too close, or that it was subject to some major disturbance.

If the angular momentum of the Sun had been derived totally independently of that of the Solar System, as for example if a disc of gas had been acquired around a star that had an independent, earlier origin, then the chance of the angle being as small as $7\frac{1}{4}°$ is only 1 in 250. On the other hand, if an originally fast-spinning Sun had given up almost all its original angular momentum to a surrounding disc that was initially in close proximity, it would be difficult to see why the material in the disc would be organized to a common plane with a scatter of not much more than 2°, and yet have the central object inclined by as much as $7\frac{1}{4}°$. (Mercury has an orbital inclination that is almost exactly the same as that of the Sun, but rotated to an arbitrary longitude by precession. Possibly Mercury formed from material that shared the angular momentum with that which formed the Sun.)

What then are the possible models of the early Solar System that are compatible with this dynamical situation? Which models are acceptable on dynamical grounds, and would accord best with the modern information concerning the chemical and isotopic composition of the planetary system?

To account for this distribution of the angular momentum, most of the published work in this subject has been concerned with an outward evolving disc, and the suggestion has been made that a magnetic coupling between the Sun and the disc mediated the angular momentum transfer, with the result that material was spiralled out as far as the region of the major planets.

There are numerous difficulties in such a scheme. No satisfactory explanation for the tilt of the Sun's axis to the planetary disc has been found. Also it has been difficult to see how the condensation of the planets from the necessarily high density material could have been delayed until the disc was flung out as far as the planets are now. The magnetic coupling mechanism would require very much stronger fields than the Sun or other similar stars seem to possess.

The latest addition to the arguments constraining the model of the early evolution comes from the isotopic evidence of the meteorites. It has become clear that the Solar System possesses material from more than one nucleogenetic source. A gaseous disc close to the Sun at an early stage would surely have become homogeneous, except for chemical sorting and the small effects of isotopic fractionation, and this would not account for the differences now seen. Later capture from space of non-indigenous material has been suggested, but the detailed meteorite evidence does not seem to accord with this. Isotopically 'anomalous' material is present in chunks as much as centimetres in size, and one can see no way in which material from outside the Solar System could have been captured as chunks, or concentrated to end up as many 'foreign' chunks in a matrix of 'indigenous' material.

The alternative basic model is one of an inward-spiralling disc, presumably initiated by a dense gas cloud, such as the molecular clouds with which one is now familiar. Can such a model satisfy the requirements of the dynamics, as well as of the chemical and isotopic evidence?

For such a system the possession of the large amount of angular momentum around the common centre of gravity would not be any anomaly. A contracting cloud, starting from less dense and necessarily turbulent galactic material, would be expected to have much material endowed with specific angular momentum comparable with that of the major planets. The anomaly that has to be explained lies entirely in the low angular momentum of the large quantity of solar material.

A disc in which the material slowly spirals inwards appears to be the only way in which the high density of the Solar System can be reached from initially turbulent galactic clouds. Any contraction from galactic densities to the mean density of the Solar System would leave the material with sufficient angular momentum for this to be a constraint for further contraction. Any form of friction within such a disc leads to a dynamical evolution where much material spirals inwards, as angular momentum is transferred outwards by this friction. One could see that a massive central body would gradually accumulate in the centre. The expected period of its rotation would then be defined by a build-up process, where each unit of material is added with the orbital velocity at the equator of this growing body. If such a body had the size of the Sun, one would calculate a period of approximately 3 hours for the rotation, and not 28 days.

The obliquity of the solar axis would be no problem in such a model. It would be entirely reasonable to assume that friction had brought the disc to an almost plane, but not quite plane, configuration at the stage at which the Sun was being built up, but that further friction in the disc still allowed more precise flattening of the remainder. An almost, but not precise, coincidence of the rotation axes seems a probable result of such a process, but it is the rotation speed which would have been predicted to be 220 times faster.

The problem of the slow rotation of the Sun is compounded by the fact that most solar-type stars appear to be slow rotators also. Whatever explanation is offered for the Sun ought, presumably, to be a sufficiently general one to be applicable to the majority of stars of this type. It may well be an explanation that involves the possession of a planetary system by all those slowly rotating stars that are not binaries, since in such a scheme it seems probable that a disc would be left over after the formation of the central body.

The suggestion I have made is that the central body starts its growth as a degenerate object and becomes a luminous star only late in its accretion process. In this picture one has first a disc that possesses too much angular momentum for any central object to form. As friction withdraws energy from the differential rotation, some material gradually spirals to the centre. A cool, small body will form, and it will continue to grow with the inward-spiralling material always being added from a close equatorial orbit. As such a body accumulates more mass, it will become a high-density, degenerate object. Matter that is added throughout this accretion process will always possess the low specific angular momentum appropriate to a close equatorial orbit around a high-density dwarf star. If then, at a late stage in the accretion process, the temperature and pressure in the interior reach sufficient values to cause nuclear ignition of the hydrogen, enough energy becomes available to lift the body out of the degeneracy and to bring it, after a period of violent oscillations, eventually to the configuration of a Main Sequence star. The star now possesses the low value of angular momentum per unit mass of its earlier configuration, and now, expanded to its large size, it must spin very slowly.

The value of the mass at which nuclear ignition will set in will depend on the rate of accretion. In the interior, heat is liberated by the compression, and lost by conduction to the surface. The faster the accretion rate, the higher will be the internal temperature, and the smaller will be the mass at which ignition occurs. Perhaps all stars formed by starting out as cool, degenerate objects but with a large scatter in the value of the mass at ignition, depending on the chance dynamics of the cloud from which they form. When the mass gets large enough (and we do not know the critical value yet), the conditions for ignition become overwhelmingly favourable because of the high pressure, the high temperature rise due to compression, and the slower rate of loss of heat. One could therefore speculate that it is rare for stars to become much more massive than the Sun and still remain degenerate. If there is still a lot more mass to be added, then it will again be from an equatorial orbit, but for the large dimension of the star, it now represents a much larger amount of specific angular momentum. The growth at this stage, therefore, will spin up the star. This could account for the well known fact that stars that are much more massive than the Sun mostly seem to be fast rotators, while stars of the solar type and below have this strange low rotation speed.

While this explanation would account in general for slow rotation speeds of small stars, it must be said, however, that in a detailed calculation it is difficult to get to quite such a low rotation speed as that of the Sun. A rotation period of five days could be readily accounted for. One can argue of course that the inward-spiralling material coming from an extended turbulent cloud brings in something more akin to a succession of rings of different inclination, rather than a coherent disc. And in that case the net angular momentum gained by the growing body can be lower. Perhaps some magnetic drag can be invoked also, both in the degenerate phase and later. In any case, the discrepancy is only a factor 5 or so, rather than a factor of 220, which is involved in the case of a sun accreting without going through the degeneracy phase.

The manner in which a turbulent gas cloud would contract under its self-gravitation and internal energy loss has not yet received much attention. One discusses a contraction as a ball, and then, at a later stage, as an object flattened because of its net angular momentum. But no attempt has yet been made to see whether the internal dissipation processes would really take the system from a turbulent cloud to a differentially rotating oblate spheroid. Quite different configurations seem possible.

The dynamical dissipation in a turbulent cloud is due to two different physical processes. One process is the creation of pressure fluctuations of a magnitude of the general order of the density multiplied by the square of the turbulent velocities that occur. The adiabatic heating then leads to radiation, which is largely lost from the system. The other mechanism is one of friction due to turbulent viscosity, aided by magnetic interactions. Of the two processes the former is generally the one acting more quickly. If that is so, then a turbulent cloud may reduce its turbulent motions in the specific way in which fluctuations in pressure are minimized. A differentially rotating disc would indeed be a possible end product, but it is not the most general one. Which is the system that possesses the least amount of organization necessary to avoid fluctuations of the pressure? It is clear that intersecting orbits would be combed out, since they will make gas masses clash, and therefore result in pressure variations. This consideration will remove non-circular orbits as the system becomes centrally condensed. Inclined circular orbits remain a possibility, so long as no two intersect, and that will be true provided no two have the same radius. Instead of a flat disc made up of circular orbits, we can have a configuration of rings of different sizes in a great variety of inclinations. Once the system has achieved this type of configuration it will shrink at a lower rate only, as given by the viscous interactions that remain.

Probably a disc that is warped, but nevertheless continuous as one goes out from the centre on its surface, is the shape to be expected. The warping may be so severe that the orientations far out bear little or no relationship to the orientations in the inner part. If looked at with a definition inadequate to recognize the warped sheet, the system may look approximately spherical. It could be that the molecular clouds in the galaxy, that appear to have reached very high densities, are configurations of this kind, and that this accounts for the failure to detect the pattern of motion that would correspond to a rotating disc.

The inner part of the forming Solar System may have been brought to a common plane by friction between the successive rings, as the inclination precesses in the quadrupole field of the neighbours; but there may be an outer part for which the timescale for flattening to a common plane would have been far too long for this to have occurred.

One may speculate that the Oort Cloud of cometary material had its origin in such an outer domain. There has always been the problem of how material could have condensed into solids in a part of space where the mean density was extremely low. The rings may provide the answer. At any one radius a ring of gas, and grains that have condensed from it, would be expected to flatten down into its mean plane. A high density can be achieved locally and lead to the coagulation of substantial bodies. Such bodies may later be subjected to perturbations that place them on a variety of orbits, but now the probabilities of collisions between them are very small and long lifetimes are possible.

One could then perhaps also understand how meteorites containing two different nuclear mixes could have been assembled. The cloud may never have become homogenized before the setting up of the ring system, and different rings may then represent a different nuclear composition, possibly including an addition from a nearby supernova. After the material had condensed into larger objects, and later had been put on a variety of orbits, material from two such bodies may have been assembled into a single one. This body could then contain discrete units, arising from each of the two nuclear mixes.

Modern information points to the formation of a planetary system by slow inward evolution of a cloud, rather than by the outward evolution of an originally dense system. In any case a dense system must have been preceded by an inward evolution, and the evidence we now have does not seem to make the case that the system ever went through this intermediate compact phase.

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Discussion

H. ZINNECKER (*Royal Observatory, Edinburgh, U.K.*). In Professor Gold's picture of cold accumulation it would seem that stars approach the Main Sequence from below rather than from above along the Hayashi track. How does he then explain the well known observational fact (see, for example, Cohen & Kuhi 1979) that pre-Main Sequence stars are located *above* the Main Sequence?

Reference

Cohen, M. & Kuhi, L. V. 1979 *Astrophys. J. Suppl. Ser.* **41**, 743–843.

T. Gold. The stars can be seen only after they have lit up, and at that stage they will overshoot and oscillate before settling down into the Main Sequence equilibrium configuration.

W. H. McCrea, F.R.S. (*Astronomy Centre, University of Sussex, Brighton, U.K.*). Professor Gold spoke of material 'trickling' (which I think was the description he gave) into a forming star from interstellar matter spiralling inwards in some plane through the star. I should like to ask why he does not consider fragments of material simply falling directly from the interstellar cloud concerned into the stars of a forming cluster, without the requirement of setting up this spiralling motion.

Like others, he apparently envisages the approximately simultaneous formation of stars in a cluster of a few hundred members; at the same time he speaks of the flattening of the interstellar material into some sort of 'pancake'. Would he care to amplify his picture? In particular does he see all these stars being formed from a single 'pancake', or is there to be a different flattened spiral for each star? It seems that the two possibilities could be very different from the point of view of the allocation of the total angular momentum of the material.

T. Gold. Fragments from the interstellar cloud will only very rarely have so little angular momentum relative to the forming star, that they could just fall in. Most material can only join the central object after friction in a disc has systematically removed angular momentum from the innermost part of this disc.

On a large scale of a cloud that forms many stars, I do not see the possibility of flattening down to a common plane. Different components of a turbulent cloud must have a motion which is more poorly organized. It is only on a small scale, comparable with that of the Solar System, that friction and precessional motion can be expected to lead to sufficiently short timescales for flattening to a common plane to be achieved.

R. J. Tayler (*Astronomy Centre, University of Sussex, Brighton, U.K.*). If Professor Gold's model is to be applied to the formation of stars in general and if the formation is slow, there would seem to be a possibility that the spread in time of formation of stars in a cluster would be much larger than is usually assumed and that it might give problems with observed Hertzsprung–Russell diagrams.

T. Gold. This must certainly place a limitation on the spread of the condensation times; but it surely will allow a much longer formation time than has generally been assumed for the alternative formation process. A timescale of a few tens of millions of years would help with the nuclear evidence in the case of our Solar System.

R. J. Tayler. I would guess that up to a few times 10^7 years might be acceptable. According to a rough estimate that I have just made, if one requires most of a solar mass accumulated as a degenerate star, the lifting of degeneracy might lead to a temperature high enough for helium burning. Does Professor Gold have any views on this?

T. Gold. An interesting possibility.

M. M. Woolfson, F.R.S. (*Department of Physics, University of York, Heslington, York, U.K.*). If it is postulated that the Sun grew slowly, then it is reasonable to suppose that the initial stage of growth of a more massive star was also slow. The process of adding mass from 1 $M_\odot$, at which time the Sun would be in much its present state, to, say, 10 $M_\odot$ would add much more angular momentum than is actually observed. As I mentioned in my talk, even the addition of one Jupiter mass in orbit around the solar equator would contribute three times the Sun's present angular momentum.

T. Gold. The massive stars are spinning fast, with an angular momentum not much below the stability limit, and some appear to be right at this limit.

One hundred times the solar value of the angular momentum per unit mass is not rare among stars of ten solar masses.

D. O. Gough (*Institute of Astronomy*, *Madingley Road*, *Cambridge*, *U.K.*). One of the consequences of Professor Gold's scenario is that today in the core of the Sun there is a greater abundance of heavy elements than standard theory predicts. It is interesting that the small frequency differences between pairs of high-order low-degree p modes whose orders differ by unity and whose degrees differ (in the opposite sense) by two, are now observed to be somewhat lower than the theoretical predictions. It can be shown that this implies a rather sharper decline in the sound speed towards the centre than there is in a conventional solar model. A greater abundance of heavy elements would produce this. One possibility is that the Sun is older than is generally believed (here I measure age in units of the Main Sequence lifetime), but Professor Gold has provided another. I would guess, however, that Professor Gold would require there to have been substantial mixing between core and envelope during the T Tauri phase, for otherwise the p-mode frequency separation would now be too small.

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