IMPLICATIONS OF AXIAL SPIN, SPIN ATTENUATION, AND ORBITAL ENERGY ON THE PLANETS AND STARS ON SOLAR SYSTEM FORMATION. A. M. Hofmeister[1] and R. E. Criss[1], [1]Department of Earth and Planetary Science, Washington University, St. Louis, MO 63130 USA (hofmeist@wustl.edu).

Summary: Rotational energies of stars and planets show that accretion converts gravitational potential mostly to kinetic energy, not heat. Dust collapse is key.

Introduction: The fundamental and shared rotational characteristics of the Solar System (nearly circular, co-planar orbits and mostly upright axial spins) record conditions of origin, yet are not explained by prevailing 2-d disk models. Also, recent measurements show that young stars spin extremely fast, yet this information is not considered in existing models of nebula contraction. Formation models for both planets and stars rest on Kelvin's erroneous explaination for production of starlight (heat) via graviational contraction, and do not conserve angular momentum. We model accretion based on orbital and axial spin data and thermodynamic laws [1]. From measurements on populations of stars, we extract the time dependence of spin-down using statistical analysis [2].

Spin of the Solar System: Current planetary spin (Fig. 1) linearly depends on gravitational self-potential (U_g) of formation suggesting mechanical energy conservation [1]. These strongly correlated quantities are fully independent per their definitions:

$$\text{R.E.}_{\text{spin}} = \tfrac{1}{2} I \omega^2 \text{ and } \quad U_g = -\frac{3}{5}\frac{GM^2}{R} \quad (1)$$

where I is the moment of inertia, ω is angular velocity, G is Newton's constant, M is mass, and R is its radius.

Initial spin of the formed gas giants are indicated by balancing the draw of the nebula to a protoplanetary nucleus against the draw toward the accreting Sun:

$$\left(\frac{r_{\text{cloud}}}{r_{\text{orbit}}}\right)^2 \le \frac{M}{M_{\text{central}}} \quad (2)$$

This agrees with sizes of satellite orbits and falls on the 1:1 line, indicating mechanical energy conservation.

Data on yellow stars in open clusters trend towards U_g=-R.E. (Fig. 1). Our estimate for the initial spin of the Sun (a few hours) lies on the line defined by the planets. Similarly fast spins have been observed for young stars of diverse mass, e.g., [3].

Energy conservation: Because the independent variables during contraction of the nebula are volume and temperature (T), the Helmholtz free energy is requied for thermodynamic analysis. The result is:

$$\Delta U_g = -\Delta\text{R.E.} + S_f\Delta T + T_i\Delta S \quad (3)$$

where S is entropy (i.e., uncompensated heat). For several reasons, T rises insignificantly. Foremost, because ΔU_g is negative per Newton's law, and if no other changes occur, ΔT must be negative. Positive ΔT is only possible if the other terms on the right side of Eq. 3 are negative and offset ΔU_g, in which case -ΔR.E. (and possibly $T_i\Delta S$) accounts for negative changes in gravitational potential. Hence, the postulated temperature rise is superfluous. Because T is low in the nebula, the entropy terms can be neglected, providing:

$$\Delta U_g \cong -\Delta\text{R.E.} \quad (4)$$

Heat lost to the surroundings upholds the 2nd law, see [1]. Eq. 4 agrees with Fig. 1 because the deltas are not needed, due to the low energy of the initial state.

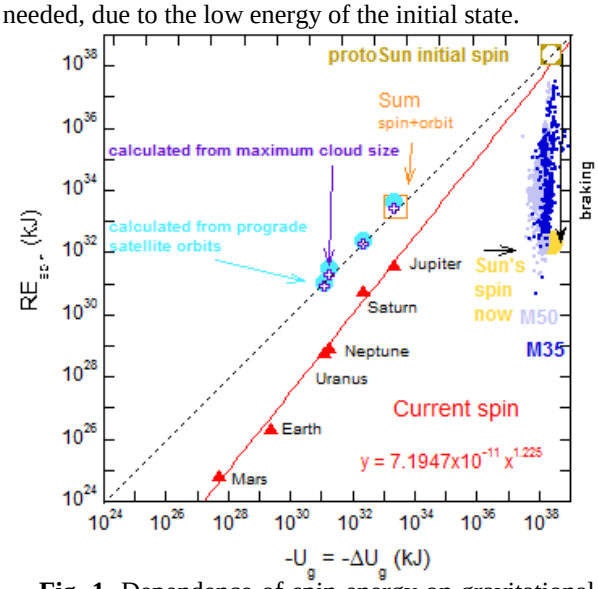

Fig. 1. Dependence of spin energy on gravitational potential energy of formation. Current spin for planets (red triangles) projects to protoSun (tan). Large yellow dot = Sun's present R.E. Blue dots = M35 spin data [4]. Lilac dots = M50 spin data [5]. Initial $\text{R.E.}_{\text{spin}}$ calculated from balancing attractive forces of the Sun and each gas giant (aqua circles) or satellite orbits (open crosses). Venus and Mercury now spin synchronously so their energies are not germane. The sum of orbital and spin energies at formation for the Solar System (open square) are controlled by Jupiter.

Why no Heating? In the astronomy literature, U_g is taken as the total energy, which is incorrect since all stars, clouds, and planets spin with huge energies (Fig. 1), and internal heating is assumed, resulting in the absurd postulate of negative heat capacity for the contracting nebula. This is impossible because nebulae are dilute gasses which have positive heat capacity. If a nebula somehow had negative heat capacity, it could cool below 0 K upon receipt of light-energy from nearby stars. Negative heat capacity thus violates the 0th law. Also, its gas molecules are too far apart to provide

frictional heating until contraction produced a protostar (e.g., radius ~Mercury's orbit for a solar mass). Thus, no mechanism exists to provide heat.

For the rocky planets, spin is less important, but their orbital energies are larger than their U_g. The excess is explained by contraction of their orbits by ~20% during accretion and is further consistent with conservation of angular momentum [1]. Heating is minor, and would have occurred via surface collisions, after the bodies were formed from collapse of the dusty nebulae.

Collapse of Dust: As the solar nebula slowly contracted, collapse of pre-solar dust in spheroidal shells simultaneously formed rocky protoplanets embedded in a debris disk, creating nearly circular co-planar orbits and upright axial spins with the same sense as orbital rotation, which were then enhanced via subsequent contraction of local nebula material. Because rocky kernels at great distance out-competed the pull of the co-accreting star, gas giants formed in the outer reaches. The nebula imploded, once constricted to within Jupiter's orbit. Afterwards, disk debris slowly spiraled toward the protoSun, cratering and heating intercepted surfaces. Our 3-d model [1] conserves energy and angular momentum (L), allows for different behaviors of gas and dust, and explains key Solar System characteristics (spin, orbits, gas giants) and other features (dwarf planets, comet mineralogy, satellite system sizes).

Angular Momentum and Giant Impacts: A giant impact on Earth is inconsistent with Earth's orbit being near-circular, in plane, and concentric with other planet's orbits, and with Earth spinning nearly upright, like most planets, and at a similar rate. Instead, late stage impacts far more frequently occured on our Moon than on Earth (by 16×) due to the large cross section presented by the Moon's orbit to disk debris attracted to the Sun. A single impact with M=2.3×10^{17} kg at 30 km/s would alter L of the Moon by 10%. The large craters on the Moon suggest many such additions, totalling >10^{19} kg and providing a topcoat. Proven impacts on the Moon not only disturbed the angular momentum of the Earth-Moon system (which was the motivation for the giant impact hypothesis) but also provided a different surficial composition than the Earth.

Spin of Stars in Open Clusters: Spin data on dwarf stars in open clusters are now abundant, permitting quantitative analysis. Loss of angular velocity ($\omega=2\pi/\Pi$ where Π is spin period) with time (t) is described by the general form:

$$\frac{\partial\omega}{\partial t} = -\alpha\omega^n \qquad (5)$$

The solution [2] for counts (N) in histogram bins is:

$$N(\omega) = \frac{\Delta\omega}{\beta\omega^n} \quad \text{or} \quad N(\Pi) = (2\pi)^{1-n}\frac{\Delta\Pi}{\beta}\Pi^{n-2} \qquad (6)$$

Paired histograms for 8 individual clusters each having >240 measured members and different ages have strongly skewed distributions in both ω and Π. The data (e.g., [4,5], Fig. 2) are inconsistent with star formation being coeval with a spread in initial spin but uniquely indicate exponential decay (n=1 in Eq 5). Fitting provides n=1.1±0.25, which rules out Skumanich's law (n=3). Our analysis is independent of initial spin and presumes only that the rate of star production is constant for each histogram. Continuous production is reasonable for tiny stars because these draw in only miniscule portions of the gas and dust residing in open clusters. We estimate isochrones for small stars by calibrating exponential decay against absolute age and spin for the sun and the trend for the youngest, fastest spinning stars. The analysis and trends similar to that of Fig. 1 show that our own Sun is not middle aged but one of the most ancient of its class.

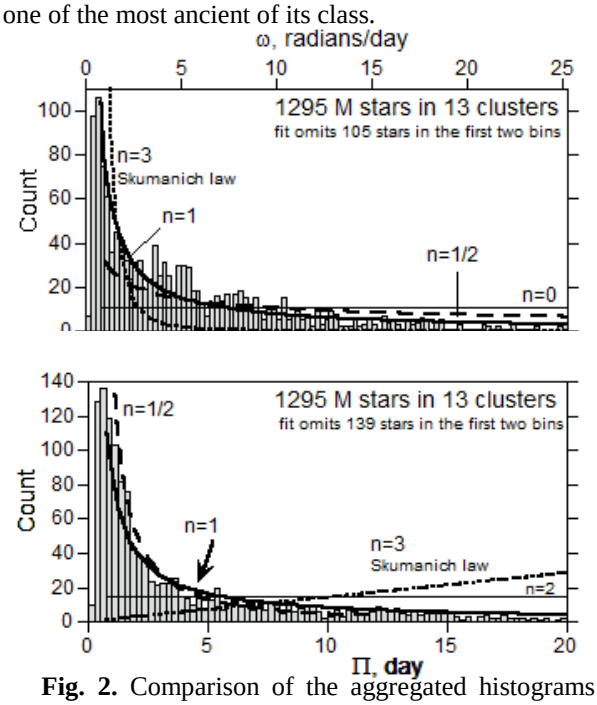

Fig. 2. Comparison of the aggregated histograms (grey) of light curve data on angular velocity (top) and periods (bottom) for stars with M<0.48M$_{sun}$ to Eq. 6 for different spin-down laws. Fits omit the first two bins, which are underpopulated. Exponential decay (heavy curve, n=1) best fits both visualizations.

References: [1] Hofmeister A. M. and Criss R. E. (2012) *Planetary & Space Science, 62*, 111–131. [2] Hofmeister A. M. and Criss R. E. (in review) *Astronomy & Computing*. [3] Dufton P. L. et al. (2011) *Astrophysical Journal, 743*, L22. [4] Meibom S., Matheiu R. D., and Stassun K. G. (2009) *Astrophysical Journal, 695*, 679-694. [5] Irwin J. et al. (2009). *Monthly Notices of the Royal Astronomical Society, 392*, 1456-1466.