FORMATION OF JUPITER'S ATMOSPHERE FROM A SUPERNOVA-CONTAMINATED MOLECULAR CLOUD. H. B. Throop[1], [1]SwRI (1050 Walnut St Ste 300, Boulder, CO 80302, throop@boulder.swri.edu)

Introduction: If Jupiter and the Sun both formed directly from the same well mixed proto-solar nebula, then their atmospheric compositions should be similar. However, direct sampling of Jupiter's troposphere indicates that it is enriched in elements such as C, N, S, Ar, Kr, and Xe by 2-6× relative to the Sun [1]. Most existing models to explain this enrichment require an extremely cold proto-solar nebula which allows these heavy elements to condense, and cannot easily explain the observed variations between these species. We find that Jupiter's atmospheric composition may be explained if the Solar System's disk heterogeneously accretes small amounts of enriched material such as supernova ejecta from the interstellar medium during Jupiter's formation. Our results are similar to, but substantially larger than, isotopic anomalies in terrestrial material that indicate the Solar System formed from multiple distinct reservoirs of material simultaneously with one or more nearby supernovas [2,3]. Such temporal and spatial heterogeneities could have been common at the time of the Solar System's formation, rather than thecloud having a purely well mixed `solar nebula' composition.

Background: Several previous models have been proposed to address Jupiter's `metallicity problem.' All are based on condensation of the volatile elements into ices, which can then be concentrated relative to hydrogen. Thes models all require an extremely cold nebula (25-35 K) at the region where the ices condensed. Such cold temperatures are difficult to achieve in some disk models, even when allowing for inward transport of ices from the outer disk. Such cold temperatures are also hard to maintain in disks in dense star clusters like the Sun's putative birth cluster, where the gas is heated by many hot stars.

Proposed Scenario: We propose an entirely different solution to the problem. Rather than forming Jupiter and the Sun from identical `Solar nebula' material and invoking condensation or transport within the nebula to modify Jupiter's composition, we propose that the composition of Jupiter and the Sun differ because of intrinsic temporal and spatial variations in the Solar nebula composition as the interstellar medium (ISM) is polluted by massive stellar winds and supernovae (SNs). We show that this model can explain Jupiter's chemical composition, easily fits into environmental formation scenarios, and is consistent with other heterogeneities in both our Solar System and distant star clusters.

In the scenario that we propose, multiple stages of star formation occurred within a giant molecular cloud (Fig. 1). The cloud was of average size, 10-20 pc, and within the GMC lay several pc-scale molecular clouds. Stars, including the Sun with its disk, began to form in clusters within these clouds. The Sun's orbit through the cluster took it on a long path several pc across. Before any nearby O/B stars turned on, the cluster environment remained cool and dark for several Myr. During this time the Sun passed through the ISM and gravitationally swept up material onto its disk by Bondi-Hoyle accretion [4]

Pollution of the ISM: The highly enriched stellar wind ejecta from red super-giant stars is heavy and slow, and can be easily incorporated into the molecular cloud without disturbing it. SN ejecta, however, moves much more rapidly and must be slowed before it can mix with the cloud. Observations show that SN ejecta is often clumpy, allowing ejecta from nearby SN (within a few tens of pc) to be slowed by the molecular cloud without dilution. Alternatively, so-called 'droplets' of SN ejecta are believed to slow and cool across kpc distances, after which they are absorbed by molecular clouds and remain as AU-scale high-metallicity concentrations within star-forming regions.

Accretion of ejecta onto the disk: Once enriched material has mixed with the ISM by either of these two methods, accretion onto the disk is straightforward. Our earlier work [4] has shown that the average ISM-to-disk accretion rate for disks in young clusters was 10^{-8} solar masses per year, or 1 MMSN/Myr. The total accretion needed in our Model B case is 10^{-4} $M_{\odot}$, or the amount delivered in ~ 10,000 years. Since accretion may be maintained for 5 Myr, this provides more than sufficient mass delivery. Due to the disk's large cross-section and its low mass compared to the Sun, accretion pollutes the disk but makes only negligible effect on the Sun's composition [5].

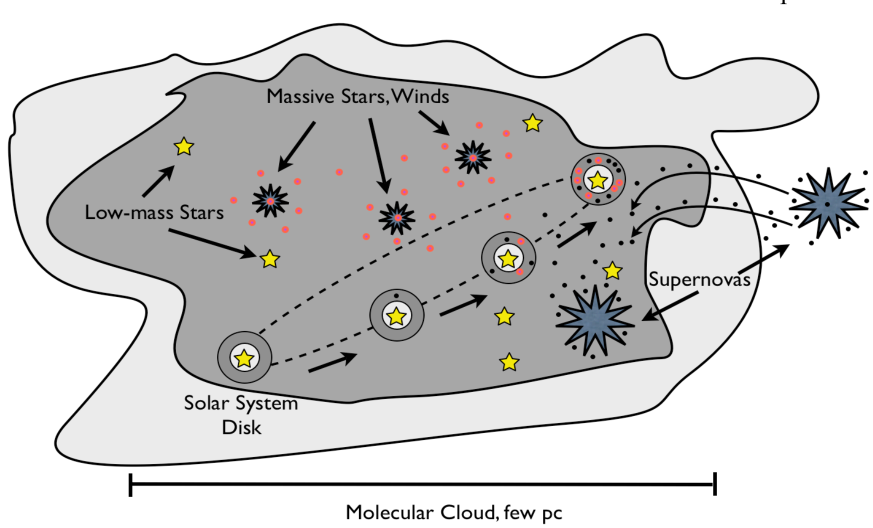
Model: We assume that Jupiter's atmosphere is composed of a mixture of three distinct components. The majority of the mass is made of Solar material, whose composition is determined by recent measurements [6,7]. The remainder is the small amounts of pollution that come from massive stellar winds and/or supernovae. The compositions of these ejecta are distinct 'fingerprints' of the stars, determined mostly by their initial mass and composition. In general, the winds of these stars are enriched primarily in light elements (C, N, O, Ne), while the SN ejecta several Myr later contain heavier species (S, Ar, Kr, Xe).

We computed linear combinations of solar material and ejecta that would produce Jupiter's measured composition. We searched all 4356 possible combinations of the 66 wind and 66 SN nucleosynthetic models of [8] coupled with the single solar abundance. For each trial, we computed coefficients that best fit Jupiter. Our routine attempted to fit only the well measured stable species (C, N, S, Ar, Kr, Xe), and computed results for both these and the remaining elements (He, O, Ne, P).

Results: Our best fit is shown in Figures 2-3. This model finds Jupiter's composition to be well described by 87% solar nebula, 9% stellar winds from a 40 $M_\odot$ star and 4% supernova ejecta from a 20 $M_\odot$ star. The total contamination is 13% (*i.e.*, 0.13 M_J). The fit is excellent at matching the observed quantities of C, S, Ar, and Kr, and the lower limit for O. The largest deviation is for N, where we are slightly below the error bar. The wind predominantly supplies C, N, and O while the SN supplies the remaining species. Both stars have high enough mass (and thus short enough lifetimes) that they can form and explode within the 10 Myr timeframe of GMCs. We assume values for the Solar and Jovian composition from [1,6,7].

Discussion: Our model has three general advantages over the existing amorphous ice and clathrate models. First, it relaxes the very strict low-temperature requirements for the formation of Jupiter's solids. Second, it allows for Jupiter to have formed at its present location without migration. Third, it explains the fact that different elements are enriched by different amounts (*i.e.*, not a uniform 3×).

Fig. 1. Cartoon view of formation scenario in which nearby massive stars pollute the ISM, enriching the disk and causing Jupiter's high metallicity relative to the Sun.



Our model reflects the growing body of evidence that the Solar System did not form from a homogeneous cloud in an isolated environment, but rather from a heterogeneous nebula where interactions with its environment played a major role in shaping its evolution.

We present additional model fits and discussion in [10].

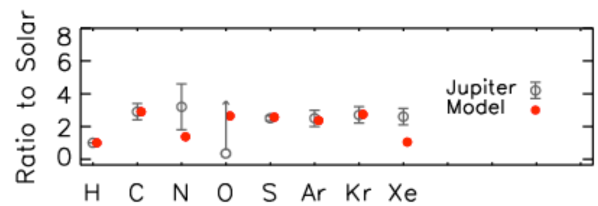


Fig. 2. Abundances of elements in our model Jupiter, compared with Galileo probe measurements.

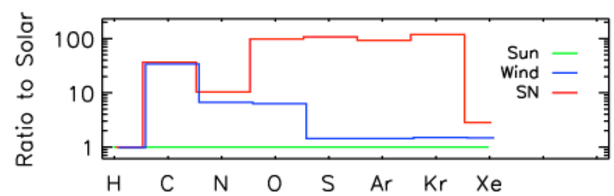


Fig. 3. Elemental abundances produced by stellar winds and supernovae. Our fit is a linear combination of the three sources shown here.

References:

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