# Accretion of Jupiter's Atmosphere from a Supernova-Contaminated Star Cluster

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## ABSTRACT

If Jupiter and the Sun both formed directly from the same well-mixed proto-solar nebula, then their observed 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 (Wong *et al.* 2007). 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 amongst these species. We find that Jupiter's atmospheric composition can be explained if the Solar System's disk accretes small amounts of mass from the interstellar medium during Jupiter's formation. The elemental abundance required matches that which can be supplied by stellar winds and supernova ejecta from the stars in a typical star cluster where the Sun is likely to have formed. The mass required is readily supplied by the small gravitational accretion of gas from the interstellar medium onto the Sun's proto-planetary disk during the several million years after the Sun forms, but before the dense interstellar gas in the star cluster has dispersed (Throop and Bally 2008). Our results are supported by isotopic measurements that indicate the Solar System formed from multiple distinct reservoirs of material simultaneously with one or more nearby supernovas (*e.g.* Trinquier *et al.* 2007). Such temporal and spatial heterogeneities could have been common at the time of the Solar System's formation, rather than the cloud being of well-mixed 'solar nebula' composition.

## 1. Introduction

The Solar System's present-day composition is thought to broadly reflects that of the initial cloud core from which it formed. On small bodies such as the terrestrial planets, subsequent thermal and chemical processes have altered the composition after formation. However, for the Solar System's two largest bodies – the Sun (mass 1 $M_{\odot}$) and Jupiter (mass 1 $M_{\rm J} \approx 0.001\ M_{\odot}$) – the atmospheric composition is relatively stable against change since the time of formation. In particular, the relative atmospheric abundances of gases C, N, S, Ar, Kr, and Xe are generally believed to be fixed at the time of formation 4.5 billion years ago, and not affected substantially by subsequent evolution. The noble gases are stable against loss due to Jupiter's high gravitational escape velocity, and stable against sinking due to condensation because they do not combine with other atomic species. Species C, N, and S combine into larger molecules such as $CH_4$, $NH_3$, and $H_2S$, but are believed to remain well-mixed in Jupiter's troposphere without settling to the interior.

Jupiter's composition in the 5–20 bar range was directly measured by the Galileo descent probe's mass spectrometer in 1995. Initial results (Atreya *et al.* 2003, hereafter A03) showed that Jupiter was enhanced by $\sim 3 \pm 1\times$ relative to the then-current solar abundances of Anders and Grevesse (1989, hereafter AG89). More recent work has better determined the Solar abundances (Grevesse *et al.* 2007, G07), leading to revised Jupiter:Solar abundances. Somewhat surprisingly, these new results have actually increased the scatter between the elements, which now lie in the broader range of $4 \pm 2\times$ (Wong *et al.* 2007, WLA07). The largest change occurred in the abundance of Jovian Ar, which nearly doubled in abundance to $5.4 \pm 1.1\times$ solar. All enrichments in this paper are in terms of number density relative to hydrogen, normalized to the Sun; *i.e.*, $(n_i/n_H)/(n_i/n_H)_{\rm sun}$.

## 2. Previous models

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 the hydrogen gas. The 'amorphous ice model' (Owen and Encrenaz 2006; Owen *et al.* 1999) proposes that Jupiter's atmosphere was formed from a combination of solar nebula material and 'solar composition icy planetesimals' (SCIPs). The SCIPs were made of amorphous water ice in which all of the other volatile species are condensed; these SCIPs had the same composition as the Sun, except were depleted in H. Jupiter then formed from a linear combination of these two components: when SCIPs were introduced into Jupiter from the protoplanetary disk, they were heated and released their volatiles into Jupiter's atmosphere. (This two-component model is distinct from the formation of Jupiter's core, which is a separate issue.) The competing 'clathrate hydrate model' (Hersant *et al.* 2004) uses a similar approach, but proposes that the volatiles are trapped within clathrate hydrates, rather than amorphous water ice. In this model, species condense out as the nebula slowly cools to their clathration temperature. Because water can condense first and trap volatiles later, the process can work over a broader range of thermal histories (and slightly warmer) than the amorphous ice model. The clathrate model has a condensation order which resembles the Jovian abundance. Both models have the appeal of simplicity and directness.

These models share two problems. First, in order for volatiles to condense, the nebula must be very cold. The condensation temperatures required are very cold: $\lesssim$30 K for the noble gases onto amorphous ice or into solids, and 5–25 K warmer for clathrate hydrates. The clathrate models assume very cold nebula temperatures of $<$20 K at 5 AU at several Myr. These temperatures are extremely low compared with thermal observations of disks, which show temperatures of $20 - 50$ K at 50 AU, and much warmer inward (Watson *et al.* 2007). Disk models show that these low temperatures may be reached only in the case of passive disks not undergoing accretion (Chiang and Goldreich 1999). The low disk temperatures required are also dangerously close to – or perhaps already below – the 20–50 K gas and dust temperatures of the molecular cloud itself, which set an absolute lower limit for the disk temperatures (Johnstone and Bally 2006; Johnstone *et al.* 2006; Bally *et al.* 1991). These molecular cloud temperatures are highest in the largest clouds and those with massive stars, which are the regions most likely to be where the Solar System formed (*e.g.* Hester *et al.* 2004). Even if the nebula were to reach the proper temperature, confirmation of clathrate formation rates at solar nebula temperatures and pressures requires some additional laboratory demonstration (Iro *et al.* 2003). Further, in order for ice to trap other volatiles as clathrates, its surface must remain exposed ('microscopic' grains) for several Myr until the nebula cools (Hersant *et al.* 2004). This is inconsistent with models showing that grains grow rapidly; planetesimals up to 100 km are thought to be able to form within 1 Myr even at 30 AU (Weidenschilling 1997). Also, this existence of such small grains would work to insulate the disk and keep it warm, rather than allow it to cool to the temperatures required by clathration. Thus, the solar system's bodies may simply have formed too large, too quickly, to clathrate sufficient volatiles from the disk atmosphere.

The models do a reasonable job of fitting Jupiter's composition. The SCIP models predict a uniform enhancement of 3$\times$ in all species, fitting the original Galileo data very well. However, no SCIPs have ever been identified in the Solar System, so the origin of these bodies is unknown. Comets, for instance, are depleted substantially in N and are of decidedly non-SCIP composition (Iro *et al.* 2003). The clathrate models result in too much S (by a factor 2$\times$) and predict a Jovian O:H ratio of $\sim 10\times$, because volatiles are trapped by the clathrate mechanism with less efficiency than they are into amorphous water ice. All of the models attempt to fit the roughly $3 \pm 1\times$ enhancement of the original Galileo values, and do not try to fit the newer $4 \pm 2\times$ values; Owen and Encrenaz (2006) dismisses the revised values as being possibly due to systematic errors. The revised Ar value of $5.4 \pm 1.1\times$ is more than double the previous value of $2.5 \pm 0.5\times$, and none of the models fit this well. Interestingly, Ar has in fact the *coldest* condensation temperature (∼35 K into clathrates, and 20 K as a solid) of all the species measured, making its high abundance of particular challenge to all the condensation models.

Guillot and Hueso (2006) uses photo-evaporation and viscous migration of the entire nebula to explain Jupiter's enrichment. In this work, UV flux from internal and/or external stars heats and preferentially removes hydrogen from the inner proto-planetary disk, leaving behind planetesimals which have grown and condensed to the midplane where they are protected. These planetesimals then migrate inward where they heat and go into forming Jupiter. This model is appealing, and consistent with the idea that the young solar system may have experienced the effects of nearby massive stars (*e.g.*, Tachibana and Huss 2003; Throop *et al.* 2001). It shares the problems of the other models in that it requires a cold nebula, although the planetesimals form much further out and evolve inward to 5 AU to replace gas removed by photo-evaporation. The disk temperatures still must be lower than the cloud temperatures; this is arguably less likely in a dense star cluster heated by recent generations of stars. The model also assumes a quite heavy initial disk mass of ∼25 MMSN.

Two other models also deserve mention. The 'tar' model by Lodders (2004) proposes that Jupiter formed from carbon-rich (rather than ice-rich) planetesimals. However, this scenario depends on the assumption that the Galileo probe sampled a typical region of Jupiter's atmosphere, and most work supports the opposite view that the probe hit an anomalously dry spot. Finally, work by Alibert *et al.* (2005) explores the possibility that Jupiter formed at 10–15 AU in a colder portion of the nebula, and then migrated inward. The migration rates must be carefully tuned to prevent Jupiter from continuing in toward the Sun, however, and may be unrealistic (Lissauer and Stevenson 2007). This work also shares the problem with the other clathrate hydrate approaches that the amount of water ice required predicts a very high Jovian O:H value and may require an unrealistically high Jovian core mass.

## 3. Our model

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 had a typical size of ∼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 small amounts of material onto its disk.

If the Sun was the only nearby star, then the composition of the ISM might be uniform. But in our proposed scenario, other clusters nearby formed a few Myr earlier, some with higher-mass stars, and the ISM surrounding these clusters soon began to be polluted in heavy elements by stellar winds and SNs from these more massive stars. Nucleosynthesis in these stars enriches their ejecta by $\sim 100\times$ or more relative to Solar H. The Sun's evolving orbit took it through these other more polluted regions of the ISM. Material was accreted onto both the Sun and its disk, but the disk's larger cross-section and lower mass made it far easier to pollute than the Sun. The disk's metallicity slowly increased, and Jupiter's core and atmosphere formed from the disk. The disk dispersed within 5–10 Myr, around the same time as the local ISM dispersed and the cluster spread apart, ejecting the Sun as an unbound field star. Jupiter's final composition thus represented largely the same material as the Sun, but with the late accretion of polluted material accounting for Jupiter's enriched composition today.

Our proposed model reflects much of the current understanding of star formation in large clusters and molecular clouds (*e.g.* Bally 2008). Stars do not form in isolation, the ISM is not of uniform composition, stars travel on long orbits through their young clusters, and material from the ISM can be accreted onto young stars and disks in the several Myr after they form. All of these are newly appreciated processes that have not been incorporated into existing models of Solar System formation. We find Jupiter's metallicity to be one natural consequence of these processes, and we explore here the issues involved with it. In the following sections we examine first the detailed chemical constraints on Jupiter's composition from such a model (§4), and the timing and spatial parameters required (§5). In §6 we describe several other examples where pollution from stars is known to occur, including existing evidence based on heterogeneities in our own Solar System.

## 4. Chemical constraints

In this section we investigate the detailed chemical enrichment from this 'polluted accretion' process and whether it can explain much of Jupiter's current composition.

We start by assuming 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 well-determined by the measurements of G07 and AG89. The remainder is then the small amounts of pollution that come from massive stellar winds and/or supernovae. The composition of these ejecta are distinct 'fingerprints' of the stars, determined by their initial mass, their composition, and a handful of other parameters. 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). As one example, the demise of a star with an initial mass of 23 $M_\odot$ can produce 5 $M_\odot$ of O, 0.5 $M_\odot$ of C, 0.2 $M_\odot$ of Si, 0.001 $M_\odot$ of $^{26}$Al, and $10^{-4}$ $M_\odot$ of $^{60}$Fe in its SN phase (Young and Fryer 2007). In our models, we use the grid of nucleosynthetic ejecta computed computed by Woosley and Heger (2007, hereafter WH07). These models span the mass range 12–40 $M_\odot$, and consider a variety of values for nucleosynthesis rate coefficients and explosion energy parameters, for a total of 66 models. Each of these models provides yields for the stellar winds and SN ejecta.

We denote the elemental abundances in the Solar, wind, and SN components as $n_{\rm sol}$, $n_{\rm wind}$, and $n_{\rm SN}$; the Jupiter abundance is $n_{\rm Jup}$. It is then possible to calculate model Jupiter compositions by using

$$n_{\rm Jup,i} = f_{\rm sol}\, n_{\rm sol,i} + f_{\rm wind}\, n_{\rm wind,i} + f_{\rm sn}\, n_{\rm sn,i}, \tag{1}$$

where $i$ is the species and $f_{\rm sol} + f_{\rm sn} + f_{\rm wind} = 1$. We use the present-day solar abundance, but the difference between this and the Sun's primordial composition is insignificant for our purposes.

Using Eq. 1, we searched for combinations of solar material and ejecta that would yield Jupiter's composition. We searched all $66^2 = 4356$ possible combinations of the 66 wind and 66 SN models of WH07 coupled with the single solar abundance. For each trial, we computed coefficients which best fit Jupiter. Our fit routine attempted to fit only the well-measured species (C, N, S, Ar, Kr, Xe), but computed results for both these and the remaining elements.

Our best fit ('Model A') 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 (WH07's model `s40a28A`), and 4% supernova ejecta from a 20 $M_\odot$ star (WH07's `s20a37n`). The total contamination is 13% (*i.e.*, 0.13 $M_{\rm J}$). The fit is excellent at matching the observed quantities of C, S, Ar, Kr, and Xe, 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 the latest G07 and W07 values for the Solar and Jovian composition.

An alternate fit is shown in Figures 4–5 ('Model B'). This model differs in that we have used the abundances of AG89 and A03 for $n_{\rm sol}$ and $n_{\rm Jup}$. Although the newer abundances are probably preferred, using the old ones gives a test of the robustness of our fits. Also, the nucleosynthetic yields of WH07 start with the AG89 solar abundances, so in a sense this fit is more self-consistent, even though it is based on slightly older data. Model B requires about 6% total contamination, less than half that required by Model A. Model B is comprised of 94% solar, 4% stellar winds from a 40 $M_\odot$ star (`s40a28A`), and 1.5% SN ejecta from a star of original mass 25 $M_\odot$ (`s25a41d`). All species are fit well except for Xe, of which our model produces only small amounts.

Both of our fits look quite reasonable. In both cases the vast majority of Jupiter's mass comes from the Solar nebula. And in both, a combination of winds and SN – which one would expect in a realistic cluster – works better than any single component by itself. The largest difference between the two results is in the SN C:N ratio, which is several times higher in Model B. The great deal of C ejected by the Model B SN allows the total contamination in this model to be about half that in Model A.

Detailed yields from our two models are listed in Table 1. This table lists additional species measured by Galileo but which are not in equilibrium at the entry site and thus not expected to fit: He, Ne, and P. He and Ne are believed to combine into He-Ne 'raindrops' which sink to Jupiter's interior, and cannot be used as a constraint (Roulston and Stevenson 1995). He itself is produced by the Sun so its primordial Solar abundance cannot be directly measured. O was measured at Jupiter but its value is believed to be anomalously low and not expected to fit. Encouragingly, our models predict primordial Jovian abundances for O, Ne, and P similar to those of the other species. The predicted values for O are 1.4 and 2.6 in the two models, in the range of global O values predicted by W07.

Several changes could improve the quality of our fits. First, we have used a simple fitting method, assuming contamination by only one wind and one supernova. In realistic star-forming regions such as Orion there are several dozen stars within a few pc all above 8 $M_{\odot}$ which will explode as SN; using multiple stars will increase the ease of fitting Jupiter's composition. Second, the SN ejecta models we use are quantized in relatively large mass bins (5 $M_{\odot}$), and all use certain common assumptions for stellar and explosion parameters. The SN ejecta yields are very model dependent; for instance, the models of Young and Fryer (2007) vary in abundance for individual species by 50% or more from those of WH07 for stars of similar mass. The WH07 yields ignore stellar rotation, which may be important (Hirschi *et al.* 2005). The most rare species – such as Xe, which our Model B is substantially under-abundant in – are particularly sensitive to stellar explosion parameters. Thus, a better understanding of SN yields could help (or hurt) our fits. Finally, we have not included physical processes in the ISM or disk such as sedimentation, concentration, or condensation, even though these could be important. For instance, of the noble gases in both models our poorest fit is for Xe, which is low by 50% and at the edge of the 1 $\sigma$ error bar. However, Xe condenses at a substantially warmer temperature than any of the other noble gases (at ∼55 K into clathrates, it is the easiest to condense), so if our model were to include condensation explicitly, it would operate in the direction to correct this deficiency. For now, however, we have intentionally chosen to keep our models simple to demonstrate the ease of fitting Jupiter's composition even with a very limited set of parameters.

## 5. Timing and spatial requirements

In this section we discuss the timing and size constraints in stellar birth environments that can lead to contamination of a protoplanetary disk and its planets. We start with an overview of the environment in which stars and planets form.

### 5.1. Molecular clouds and star clusters

Nearly all stars form in groups, with the vast majority forming in clusters of 30–3000 stars (Adams *et al.* 2006; Lada and Lada 2003). These clusters form from clouds of cool, 5–50 K molecular gas – predominantly hydrogen – that contract gravitationally to GMCs (∼10–20 pc) and then molecular clouds (∼1–5 pc) within them. Individual stars begin to form from small condensations within the cloud. Upwards of 80% of these stars are surrounded by circumstellar disks (Smith *et al.* 2004) of typical size 10–200 AU and mass 0.01–1 $M_\odot$; the planets form in 5–10 Myr from these disks. Star formation continues for a total of $\sim$ 5–10 Myr, by which time 10–30% of the gas has been consumed by star formation and 70–90% remains as dense molecular gas. After this time, the cluster disperses and stars are separated from their birth environment.

### 5.2. Accretion onto the disk

While stars are forming, they begin to circulate through the cloud on pc-scale orbits with $v \sim$ 1–5 km s$^{-1}$. As they do so, cool molecular gas in the cloud's ISM can accrete gravitationally onto the disks, at rates $\sim 10^{-8}$ $M_\odot$ yr$^{-1}$ (*i.e.*, 1 MMSN per Myr) for solar-mass stars (Throop and Bally 2008; Padoan *et al.* 2005). This 'Bondi-Hoyle' accretion (Edgar 2004; Bondi and Hoyle 1944) is robust against stellar winds, turbulence, and radiation pressure. The accretion stops when ultraviolet light from O or B stars in the cluster ionize the gas, or when the cluster has dispersed. Because the circumstellar disk (diameter $\simeq$ 10–200 AU) has a larger size than the star (diameter $\simeq$ 0.01 AU), and the gas initially has too much angular momentum to hit the star, accretion from the ISM is believed to be primarily onto the disk, not the star.

### 5.3. Contamination of the ISM Environment

The composition of the local ISM can change as the cluster evolves. Massive stars undergo nucleosynthesis, creating heavy elements which pollute the ISM. These are given off in stellar winds (during the stellar lifetime) or SNs (at the end-of-life for stars with M $> 8$ $M_\odot$). After being injected into the ISM, these highly enriched ejecta are incorporated with the next generation of star formation. The highest-mass stars are the shortest lived: for instance, the 40 $M_\odot$ stars used in our fits explode after $<$5 Myr, allowing for a full generation of star formation within the timescale of planet formation.

### 5.4. Contamination by Stellar Winds

Stars spend the majority of their lives on the main sequence. During this stage the stellar winds are weak enough that they do not pollute the cluster; for instance, the current

Solar wind is $\dot{M}_{\rm Sun} \approx 2 \times 10^{-14} M_\odot$ yr$^{-1}$ with $v \approx 400$ km s$^{-1}$. Red supergiant (RSG) stars, however, have slow, massive winds that can easily pollute the cluster. RSGs are normal post-main-sequence stars of mass 5-15 $M_\odot$ that have cooled dramatically after their main-sequence phase (T > 10,000 K to T < 3000 K), and have heavy and slow winds of $\dot{M} \approx 10^{-5}$–$10^{-4}$ $M_\odot$ yr$^{-1}$ and $v$ as low as 10 km s$^{-1}$ – ten order of magnitude more loss than the present-day Sun (Knapp and Woodhams 1993). The RSG phase lasts for 5-10% of the stellar lifetime, or typically a few $10^5$–$10^6$ yr (Schaller *et al.* 1992). For stars > 25 $M_\odot$, over half the original stellar mass can be lost during the RSG phase (Garcia-Segura *et al.* 1996). The wind velocity of 10 km s$^{-1}$ is only slightly higher than the stellar and gas velocities, so this material can readily mix with the local ISM. The abundances $n_{\rm wind}$ that we consider in § 4 are predominantly from the RSG phase. Stars of less than 20 $M_\odot$ evolve too slowly (t $\gtrsim$ 10 Myr) to enter the RSG phase within typical cluster lifetimes. Our Model A and B fits use winds from stars of 40 $M_\odot$ with lifetimes $\sim$ 5 Myr, which easily fit the timing constraints. These high-mass stars are seen in clusters of $N >$ a few thousand; an example is $\theta^1$ Ori C in the Orion Trapezium core. Smaller 8 $M_\odot$ stars are produced in clusters of $N >$ a few hundred.

### 5.5. Contamination by Supernova Ejecta

After passing through the RSG phase, stars with masses > 8 $M_\odot$ usually end their lives as SNs. The SN explosion gives off 1–5 $M_\odot$ of metal-enriched material. Typical initial ejecta speed is 10,000 km s$^{-1}$, far too fast for it to be accreted onto disks directly.

As it spreads, the ejecta mixes with the ISM until it slows and cools. In order to slow to 10 km s$^{-1}$, 1 $M_\odot$ of SN ejecta must mix with roughly 1000 $M_\odot$ of ISM (*i.e.*, a 1000:1 mixing ratio). The SN ejecta can be quite clumpy, ending high mixing ratios in some regions and lower in others. Rather than mixing uniformly, these clumps appear to be slowed as a unit and preserve their density, much like a baseball is slowed in the air without fully mixing. SPH simulations of the first few hours after the explosion of SN1987A show finger-like formations with density contrasts of several orders of magnitude (Herant and Benz 1992). Observations of pc-scale ejecta from SN1993J show asymmetric optically thick structure on AU scales or greater within a year after explosion (Wang and Hu 1994). And, observations of emission lines 700 years after the explosion of a third SN continue to find evidence for density contrasts of 100-200 in dense metal-rich bubbles within the ejecta (Williams *et al.* 2008). Additional work shows that some heterogeneity persists on even longer Myr timescales (Freyer *et al.* 2006; Kroeger *et al.* 2006). Thus, although the 1000:1 mixing ratio required to slow the SN ejecta may be the volumetric average, there are likely to be spatial variations in GMCs where the mixing ratio could be 100:1 or lower, roughly the amount of SN pollution required by our 'Model B' case.

Assuming 5 $M_\odot$ of SN ejecta mixing with 5000 $M_\odot$ of ISM, a portion of the $10^5$ $M_\odot$ GMC may be temporarily heated or sculpted by the explosion. However, the GMCs are generally robust against disruptions from such supernovae. This is evidenced by the history of the Orion region, which has probably seen dozens of supernovae in the past 12 Myr (Bally 2008), yet most of its mass remains a cool GMC. The "Barnard's Loop" feature in Orion is a 100 pc-scale expanding half-circle of remnant ejecta from previous generations of SNs and/or winds; ejecta filling the other half of this feature has likely been reabsorbed by the GMC and incorporated into the next generation of star formation.

### 5.6. Accretion of the ISM onto disks

Once material has mixed with the ISM, accretion onto the disk is simple. Throop and Bally (2008) found that the average ISM → disk accretion rate for stars in young clusters was $10^{-8} M_\odot$ yr$^{-1}$, or ∼1 MMSN per Myr. The total accretion needed in our Model B case is $0.1M_{\rm J} = 10^{-2}$ MMSN $= 10^{-4}$ $M_{\odot}$, or the amount delivered in $\sim$ 10,000 years. Since accretion may be maintained for 5 Myr, this provides more than sufficient mass delivery.

## 6. Observational Analogues

We have made the argument that Jupiter's atmosphere could be enriched by contamination from stellar ejecta. Here we give examples of other places where similar processes are believed to have happened.

### 6.1. Isotopic Heterogeneities in the Solar System

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 formed from a heterogeneous nebula where interactions with its nearby stellar environment may have played a major role in shaping its evolution.

The terrestrial bodies have been modified by scores of chemical and physical processes since their formation, so their current local compositions are not indicative of their original bulk makeup. However, most of these processes act equally on all isotopes of the same element, and therefore present-day *isotopic* differences between bodies are still indicative of primordial composition. Isotopic measurements have been made of the Earth, Mars, and numerous diverse classes of asteroids. Isotopic differences between these samples have been measured for species including Ba, Cr, S, Ti, Zi, Mb, and O (Trinquier *et al.* 2007; Ranen and Jacobsen 2006; Dauphas *et al.* 2002, and references therein). These anomalies are small ($\lesssim$ 1%) but indisputable. UV photochemistry has been invoked to explain the origin of the O variations (Lyons and Young 2005), but the remaining heterogeneities have defied explanation by known fractionation processes. Instead, they have been consistently interpreted as being of nucleosynthetic origin, resulting from the incomplete mixing of ejecta from multiple SNs in the material of the young solar nebula (Ranen and Jacobsen 2008; Trinquier *et al.* 2007; Ranen and Jacobsen 2006; Dauphas *et al.* 2002).

Additional spatial/temporal variation has been found in short-lived radioactive isotopes, allowing some constraint on the timing of the Solar System's early heterogeneity. Work by Krot *et al.* (2008) examined the heterogeneity of $^{26}$Al isotopes within Ca,Al-rich inclusions (CAIs) in the Solar System. They found differences of $> 100\times$ in primordial $^{26}$Al abundances, leading to the conclusion that there are at least two populations of CAIs: some which were formed in the presence of $^{26}$Al, and some which were not. This requires either spatial or temporal variations in the Solar System birth environment. Their preferred interpretation is that the $^{26}$Al-free CAIs were formed early (possibly during initial collapse of the Solar System), followed by late injection of $^{26}$Al from a nearby massive star. They suggested that this massive star could be the same one that injected $^{60}$Fe several Myr later after an SN explosion.

These scenarios are very similar to what we propose for Jupiter. The contamination at Jupiter is $\sim 10\times$ higher (or sometimes much more) than the isotopic anomalies in the terrestrial bodies. However, the terrestrial anomalies were formed directly from condensations in the solar nebula itself, very early in the Solar System's history. Jupiter formed over a much longer period, so it is not unexpected that it could have a greater enhancement. Bondi-Hoyle accretion covered several Myr and several pc, not just the local region of the proto-solar nebula's collapse, allowing for a greater sampling of heterogeneities in the entire region.

We note that relative to the galactic value, the entire Solar System itself exhibits a system-wide excess of 30% in $^{18}$O/$^{17}$O. This enhancement has been proposed to be due to accretion of supernova ejecta and massive stellar winds immediately prior to the proto-Solar nebula's formation (Young *et al.* 2008).

### 6.2. Compositional heterogeneity in star clusters

The Orion region is the closest nearby star-forming region with massive stars. As such, it provides an excellent example of a site where 'polluted accretion,' such as we propose for Jupiter, could be happening right now. We cannot today detect any planets in Orion, much less measure their metallicities. But, evidence for spatial heterogeneity and pollution has been directly observed in some of Orion's stars. Observations of the metallicity of 29 B, F, and G stars within Orion found abundance variations up to 4× between stars of the same age in the same subgroup (Cunha *et al.* 2000, 1998; Cunha and Lambert 1994). These variations were spatially correlated, suggesting that recent supernovae have contaminated distinct regions of the cluster. The abundance variations were seen in O and Si (which are produced by massive stars and type II SNs), but not in Fe, C, and N (which are produced to a far lesser degree, and thus would not be expected to contaminate the stars). The authors proposed that ejecta from recent SNs has been accreted onto these stars, causing their observed metallicity.

Two sites in Orion provide additional tangible examples of regions where disks could become contaminated in the next several Myr. First, the Orion Nebula itself is located directly behind the Ori-OB1c sub-group that contains the 3–5 Mya clusters NGC1980 and NGC1981. When the massive stars in this complex explode, they will be in excellent position to contaminate the Orion Nebula region and nearby portions of the L1641 cloud. Second, the $\sigma$-Ori sub-group of Ori-OB1c is located about 5 pc west of the southern part of the Orion B molecular cloud. As seen from the center of the $\sigma$-Ori cluster, the cloud subtends at least 1 sr, and when an explosion happens, it will pollute the western side of the Orion A cloud. Young stars forming from the polluted material, or older stars with disks that undergo Bondi-Hoyle accretion, will become contaminated with supernova debris.

In much older globular clusters, 'self-enrichment' of stellar metallicity by re-accretion of ejected stellar winds has long been considered important (Ventura and D'Antona 2008; Cottrell and Da Costa 1981). In these clusters, metals ejected in stellar winds are re-accreted into the atmospheres of neighboring stars. The slow winds from stars of $<10\ M_{\odot}$ are lower than the cluster escape velocity, so the wind ejecta is retained in the cluster until Bondi-Hoyle accretion incorporates them back into the stars. The stars thus experience a metallicity increase (of order a few $\times$) as they evolve.

## 7. Discussion

The model we propose here represents a substantial departure from existing models for the solution to Jupiter's 'metallicity problem.' However, it reflects the latest understandings of the environmental processes affecting star formation.

Historically, most formation models for the Solar System have assumed a homogeneous 'Solar nebula' composition. Recent work has begun to question this assumption. For instance, significant attention has been paid in the last decade to the origin of $^{60}$Fe and its accretion at the time of or immediately after Solar System formation. It is almost always believed that this is due to contamination of the Solar System with SN ejecta, although the precise method of accretion remains an area of study (Gounelle and Meibom 2008; Williams and Gaidos 2007). And, the measurements of isotopic anomalies (§ 6.1) are widely understood to be caused by spatial and/or temporal variations in the solar nebular composition. Our model builds on these points, emphasizing the fact that the composition of the solar nebula can change spatially and temporally. These changes occur during the Solar System's first 5–10 Myr, as the Sun is traveling through its birth cloud, experiencing the environmental effects of other stars.

Our model has several general advantages over the existing amorphous ice and clathrate models that we describe in § 2. It relaxes the very strict low-temperature requirements for the formation of Jupiter's solids; it allows for Jupiter to have formed at its present location without migration; and it explains the fact that different elements are enriched by different amounts.

Our model is not without problems. Our fits for N are at the edge (or a little beyond) the errors bars. N is poorly measured in the Galileo probe data, but is a major species and an important constraint. We could increase the contribution from stellar winds (which supply much of the N), but this would increase the amount of C beyond that observed. Low-mass stars of 4–8$M_{\odot}$ produce large quantities of N sufficient to solve the problem, but these stars have lifetimes of 30 Myr or more before they enter the RSG phase. The other species we are low in, Xe, has a particularly high condensation temperature which may in part explain its abundance.

Second, the amount of SN contamination required – 1.5% in our 'Model B' case – is on the high end of what can be supplied by SNs. SN ejecta must be slowed down by mixing with other material, and it is initially moving quite fast. Studies of concentration mechanisms for this ejecta as it spreads and cools would help our model, as would additional study of the species produced in a range of cool stellar winds beyond that considered here.

Most work suggests that Saturn, Uranus, and Neptune accreted their atmospheres from the disk in much the same way Jupiter did. The metallicity enrichments of the outer planets exceed Jupiter's – Uranus and Neptune have 30 times the Solar C:H ratio, for instance – suggesting that they were formed at least in part by the condensation mechanisms described in § 2. The colder nebula and slower evolution make volatile condensation easier at greater distances. However, 'accreted pollution' of the disk from the ISM would affect these planets as well. Because of their different positions in the disk and their different formation times, our model cannot *predict* the enrichment they may receive from pollution, except that it could be similar to Jupiter's. (Perhaps the outer disk, with its larger cross-section, receives more contamination, but this requires more study.) More detailed analysis of this must wait for better knowledge of their bulk atmospheric compositions, which are largely unknown today. Jupiter's oxygen composition will be probed by Juno in 2017 and will provide a discriminant between many models including our own (which predicts a global O:H ratio of $\sim 2.6\times$ Solar) and that of Lodders (2004) (which assumes $\sim 0.35\times$ solar).

Jupiter's atmosphere may have formed through a variety of processes, of which polluted accretion could be only one. For instance, N is among the most difficult species to condense in the various ice models, as it requires a temperature $\leq 30$ K (Owen *et al.* 1999). N, however, is easily supplied in the cool, slow stellar winds that we study here. Perhaps N was supplied by these winds, and other species were delivered in part by icy planetesimals from a relatively warm (T $\geq 50$ K) disk?

An advantage of the SN model is that it provides a mechanism for matching not only the chemical abundances which we study here, but also isotopic differences. It has already been shown that SNs may explain the isotopic differences seen in the Solar System's rocky bodies (§ 6.1); additional work on the isotopic differences between the Sun and Jupiter would be a natural extension of the present work. This path is particularly ripe for future study given the recent Solar composition results from the Genesis mission (*e.g.*, Wiens *et al.* 2007; Mabry *et al.* 2007).

The general process of accretion from ISM $\rightarrow$ disk $\rightarrow$ planet that we describe here has broader applications for the formation of extrasolar planets. A strong observed correlation exists between the metallicity of the host star and the existence of extrasolar planets (*e.g.*, Udry *et al.* 2007). The metallicities of the planets themselves are currently not known.

We predict that the correlation between stellar and planet metallicities will depend on the formation environment (which is itself admittedly difficult to determine). Stars that form in dense regions, in the presence of massive stars, will have the highest disk metallicities and thus the greatest chance of forming planets.

For solar-mass stars, pollution accreted late onto the *star* is hard to detect post-facto in small quantities, because it mixes with the entire stellar mass where it becomes heavily diluted. For more massive stars, however, the dilution is far less because the stars are less convective. For instance, a 2 $M_\odot$ star at 4 Myr has a convective zone only a few percent of its mass (Laughlin and Adams 1997). Any contamination accreted late onto the star will stay in this thin veneer where it can have a disproportionately large effect on the star's observed metallicity. If the disk has already begun to disperse, then it may be easier to enhance the metallicity of these high-mass *stars* rather than their *planets*.

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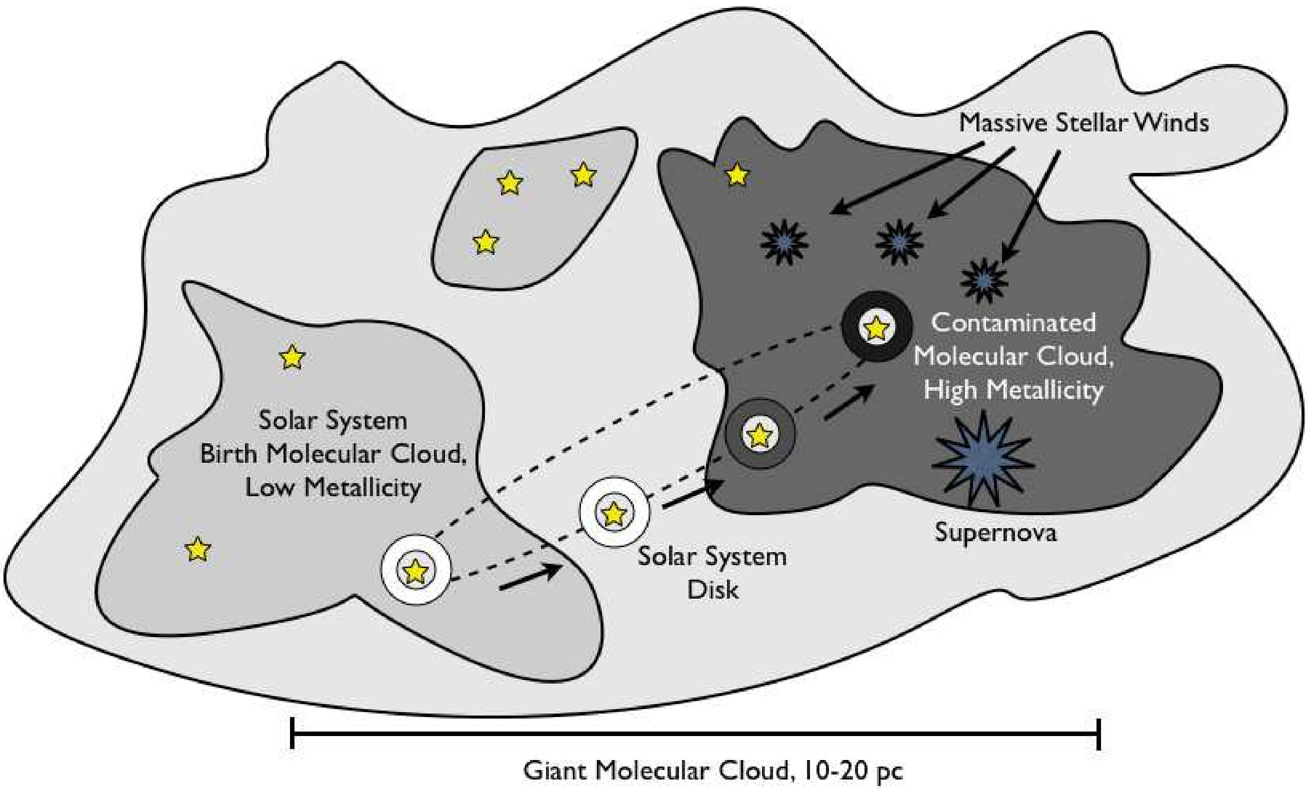


Fig. 1.— The proposed 'polluted accretion' scenario for Jupiter's atmosphere. In this model, the Sun and its disk form in a low-metallicity molecular cloud (left). The Sun's orbit takes it through other regions (right) of higher metallicity, polluted by massive stellar winds and supernovae. Ongoing Bondi-Hoyle accretion from the ISM delivers this enriched material preferentially to the disk, where it is incorporated into Jupiter's atmosphere.

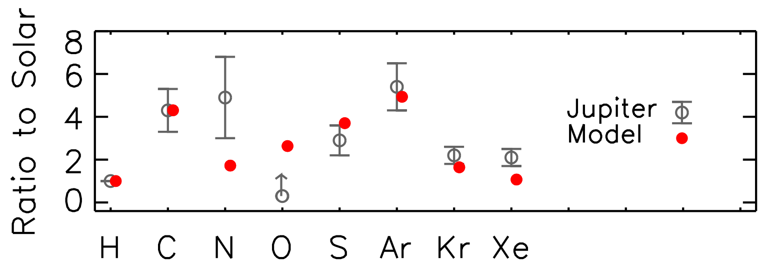


Fig. 2.— Elemental abundances of Jupiter from Galileo probe (grey), and fits for our 'Model A' case (red). The y axis plots the elemental number abundances relative to the Solar abundances, normalized to hydrogen. The model consists of a linear combination of 87% proto-solar composition, 9% from stellar winds from a 40 $M_{\odot}$ star, and 4% ejecta from an SN of original mass 20 $M_{\odot}$. O is a lower limit because the Galileo probe entered Jupiter at a cloud-free location believed to be anomalously dry. Solar and Jupiter compositions are revised 2007 values (G07, W07).

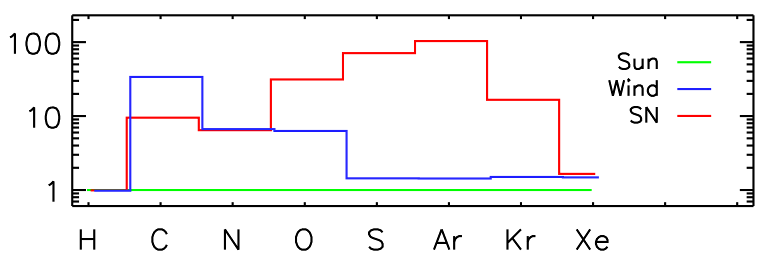


Fig. 3.— Sources of individual species in our 'Model A' case. The model is a linear combination of elemental abundances from the Sun (green curve), stellar winds (blue curve), and an SN (red curve). Each line is normalized to H at 1.0. The stellar winds produce much of the C and N, while the supernova supplies most of the remaining species.

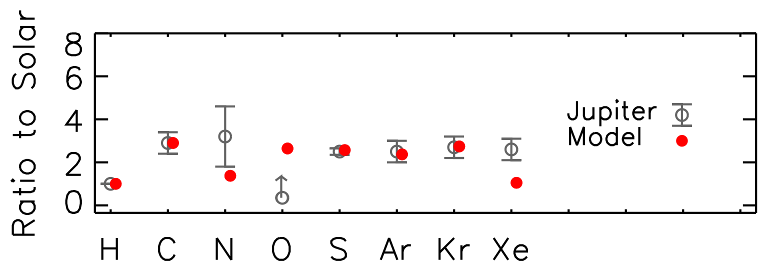


Fig. 4.— Our 'Model B' fits. Same as Figure 2, but assuming 1989 solar composition data (A03, AG89). The coefficients are Solar (94%), stellar winds from 40 $M_{\odot}$ star (4%), and a supernova from a star of original mass 25 $M_{\odot}$ (1.5%). The fractional contamination in this model is 6%, less than half that in Model A. The low predicted value for Xe might be explained by its particularly high condensation temperature (see text). The broad similarity of the results to the 'Model A' case shows that our model is robust against small changes to knowledge of the composition of the Sun and Jupiter.

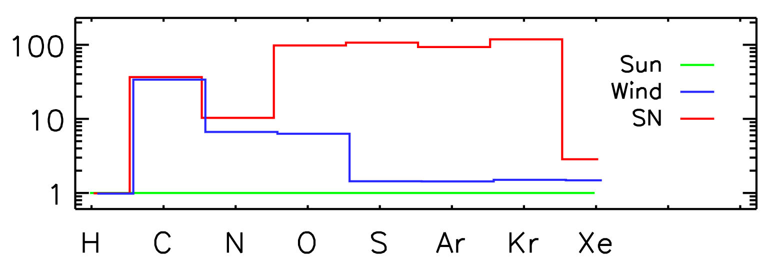


Fig. 5.— Individual components of our 'Model B' fits. Same as Figure 3, but using 1989 solar abundances (A03, AG89).

| | | Model A | | | | Model B | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species ✓= stable | Sun | Wind 12% | SN 4% | Tot | Jupiter W07 | Wind 4% | SN 1% | Tot | Jupiter A03 |
| H ✓ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| He | 1.0 | 2.1 | 2.3 | 1.15 | $0.81 \pm 0.02$ | 2.11 | 3.71 | 1.09 | $0.81 \pm 0.02$ |
| C ✓ | 1.0 | 33.9 | 9.5 | 4.3 | $4.3 \pm 1.0$ | 33.9 | 36.6 | 2.9 | $2.9 \pm 0.5$ |
| N ✓ | 1.0 | 6.7 | 6.5 | 1.7 | $4.9 \pm 1.9$ | 6.7 | 10.3 | 1.4 | $3.2 \pm 1.4$ |
| O | 1.0 | 6.3 | 31 | 2.6 | $0.3 \pm 0.2$ | 6.3 | 98 | 2.6 | $0.4 \pm 0.2$ |
| Ne | 1.0 | 3.7 | 6.7 | 1.5 | $0.1 \pm 0.1$ | 3.7 | 91.0 | 2.4 | $0.1 \pm 0.01$ |
| P | 1.0 | 1.6 | 171 | 7.5 | $0.82 \pm 0.01$ | 3.7 | 91 | 2.4 | $0.1 \pm 0.01$ |
| S ✓ | 1.0 | 1.46 | 71 | 3.7 | $2.9 \pm 0.7$ | 1.46 | 107 | 2.6 | $2.5 \pm 0.15$ |
| Ar ✓ | 1.0 | 1.45 | 103 | 5.0 | $5.4 \pm 1.1$ | 1.45 | 93 | 2.4 | $2.5 \pm 0.5$ |
| Kr ✓ | 1.0 | 1.52 | 16.7 | 1.6 | $2.2 \pm 0.4$ | 1.52 | 118 | 2.7 | $2.7 \pm 0.5$ |
| Xe ✓ | 1.0 | 1.5 | 1.7 | 1.1 | $2.1 \pm 0.4$ | 1.5 | 2.86 | 1.05 | $2.6 \pm 0.5$ |

Table 1: Details of model results, based on the listed ejecta yields from winds and SN compared with Jupiter. Table lists species observed by Galileo; abundances are in number density relative to H, normalized to Solar abundance. The checked species are those which are stable at Jupiter and our model attempts to fit; we predict the unchecked species but do not attempt to fit them. The two models are based on the two different measurements for the Jupiter:Solar abundance.

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