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# NEW INSIGHT INTO THE SOLAR SYSTEM'S TRANSITION DISK PHASE PROVIDED BY THE METAL-RICH CARBONACEOUS CHONDRITE ISHEYEVO

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## ABSTRACT

Many aspects of planet formation are controlled by the amount of gas remaining in the natal protoplanetary disks (PPDs). Infrared observations show that PPDs undergo a transition stage at several megayears, during which gas densities are reduced. Our Solar System would have experienced such a stage. However, there is currently no data that provides insight into this crucial time in our PPD's evolution. We show that the Isheyevo meteorite contains the first definitive evidence for a transition disk stage in our Solar System. Isheyevo belongs to a class of metal-rich meteorites whose components have been dated at almost 5 Myr after formation of Ca, Al-rich inclusions, and exhibits unique sedimentary layers that imply formation through gentle sedimentation. We show that such layering can occur via the gentle sweep-up of material found in the impact plume resulting from the collision of two planetesimals. Such sweep-up requires gas densities consistent with observed transition disks ($10^{-12}$–$10^{-11}$ g cm$^{-3}$). As such, Isheyevo presents the first evidence of our own transition disk and provides new constraints on the evolution of our solar nebula.

*Key words:* meteorites, meteors, meteoroids – planet–disk interactions – planets and satellites: formation – protoplanetary disks

## 1. INTRODUCTION

The main body of evidence for processes occurring during the early Solar System is found within meteorites. The combination of this evidence and theoretical modeling has led to a greater understanding of the formation and evolution of the Solar System. However, several aspects of the evolution of our protoplanetary disk (PPD) remain unresolved; in particular, the accretion of planetesimals and the formation of planets. It is generally thought that planet formation depends on the presence of gas within the disk (Kokubo & Ida 2002; Ikoma & Genda 2006), but little is known about later densities, during the so-called transition phase. This important phase in the evolution of a PPD provides information on the lifetime of the accretionary disk and disk dispersion mechanisms (Haisch et al. 2001; Hillenbrand 2005; Williams & Cieza 2011). The unusual metal-rich meteorite, Isheyevo, provides insight into this crucial phase of the early solar nebula.

The metal-rich carbonaceous chondrites (CH: ALH85085-like, CB: Bencubbin-like, and Isheyevo) are intriguing, being mixtures of chondrules, chemically zoned metals, unzoned metal, hydrated lithic clasts, and refractory inclusions, while matrix is largely absent (e.g., Weisberg et al. 2001; Krot et al. 2002; Rubin et al. 2003; Campbell et al. 2005, p. 407). The zoned Fe, Ni-metal grains are hypothesized to have formed from a vapor-melt plume produced during an impact between planetesimals (e.g., Krot et al. 2005; Olsen et al. 2013). An impact origin is consistent with the majority of components found in these chondrites. Most chondrules in metal-rich chondrites are cryptocrystalline or skeletal in texture (Scott 1988; Krot et al. 2001; Weisberg et al. 2001; Hezel et al. 2003; Rubin et al. 2003; Krot et al. 2005), and seem to have formed differently from other chondrules, based upon their inferred thermal histories (completely molten) and their young age. Although some chondrules seem to have formed contemporaneous with calcium-rich, aluminum-rich inclusions (CAIs; Connelly et al. 2012; Bollard et al. 2014), the majority have been dated to a range of disk ages 2–3 Myr after the formation of CAIs (Kurahashi et al. 2008; Villeneuve 2009). Chondrules from Isheyevo (CH/CB) chondrites formed another 3 Myr later (Krot et al. 2005, 2008; Bollard et al. 2013). Isheyevo contains lithologies characteristic of both CH and CB chondrites (Ivanova & Lorenz 2006; Ivanova et al. 2008) and phyllosilicate-bearing clasts with extreme $^{15}$N-enrichments (Greshake 2001; Krot et al. 2005, 2001; Briani et al. 2009; Bonal et al. 2010) similar to comets (Olsen et al. 2013).

Most primitive meteorites show evidence of having been compacted, fragmented, and mixed beneath their surfaces, wherein signs of primary accretion are obliterated. Evidence for accretionary growth of planetesimals is absent in our collection of extraterrestrial materials because such structures would not survive the processes associated with planetary differentiation that gave rise to the iron meteorites and achondrites. However, Isheyevo preserves primary accretionary structures delineated by a well-sorted mixture of small metal grains, chondrules, CAIs, and clay-bearing matrix lumps (Ivanova et al. 2008). The juxtaposition of fine-grained clasts that experienced extensive aqueous alteration with materials that formed at high temperature shows that Isheyevo is a mechanical mixture of disparate materials.

## 2. OBSERVATIONS

As described in detail in Garvie et al. (2015), Isheyevo preserves primary accretionary structures exemplified by prominent layering and lobe-like structures delineated by the metallic and nonmetallic components. The laminations are consistent with settling of particles that have not coagulated into aggregates. Layers richer in Fe, Ni-metal grains protrude downward into layers richer in silicate grains indicating that these are sedimentary load structures akin to those in terrestrial aqueous deposits where dense sediment is deposited over, and

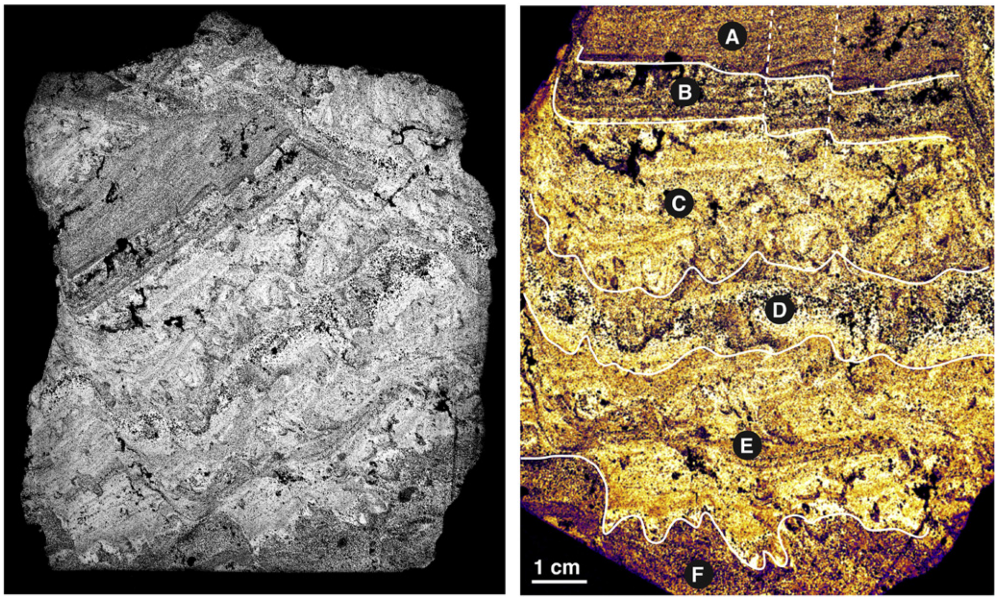

**Figure 1.** Left: photograph of a 10 × 14 cm slice of Isheyevo. Metal is white and the non-metal components are dark. Evident are the fine laminations near the top of the specimen. Right: false color image of the slice. Whites and yellows represent metal, and the darker colors correspond to the non-metallic components. Layer A is fine-grained with weakly defined laminations and B shows several alternating metal-rich and silicate-rich layers. The base of layer C is silicate rich with lobe-like structures protruding into the coarser-grained layer D. Layer E exhibits several silicate-rich layers and has a largely metal-rich base with well-developed finger-like lobes protruding into layer F. The dashed white lines delineate the faulted sediment.

protrudes into, a less dense layer (Allen 1984). The stratigraphic up position can thus be established. Also evident are faults that disrupt the planarity of the laminations and can be traced at high angles to the layering. These faults show necking and attenuation of the layers (Figure 1), suggesting that the aggregate was weakly cohesive and behaved macroscopically like soft sediment. Microscopic examination shows plastically deformed metal grains, which together with the clay clasts and chemically zoned Fe, Ni-metal grains is evidence of post sedimentary, low-temperature deformation and compaction. These stratigraphic features provide clues to the accretion and formation of the Isheyevo parent body.

Terrestrial processes that result in sedimentation, such as declining velocity in a fluid flow do not apply in this case. Therefore, layering in Isheyevo reflects accumulation of material in an accreting environment. Such layering could occur as a result of high-velocity deposition, but would result in disruption of the layers around larger impacting grains and destruction of clay clasts upon impact, which is not seen. As such, we investigate other processes that result in gentle sedimentation and layering.

The mixture of chondrules, having textures indicating rapid cooling (Campbell et al. 2005, p. 407), and metal spheres, which require cooling over days to weeks, (e.g., Goldstein et al. 2007), is consistent with formation in an impact plume (Krot et al. 2005; Olsen et al. 2013). The implication is that chondrules and metal spheres were mixed with remnants of solid material from the original impactor and then subsequently reaccreted by the surviving planetesimal on relatively short timescales. Reaccretion via gravitational settling is suggested (e.g., Asphaug et al. 2011). However, we show that gravitational settling is unlikely, and propose instead that a fan-like sheet of ejecta from the impact was slowed by gas drag and overtaken by the surviving planetesimal at speeds that allowed gentle sedimentation.

## 3. ASTROPHYSICAL SETTING

High energy impacts between large planetesimals (>300 km) could produce impact melts, but large impacting bodies would fully differentiate and would not retain hydrated clasts. Smaller bodies (~20–270 km) are more likely, but relative velocities of impact are unlikely to produce melt. However, if the smaller bodies contained $^{26}$Al at the time of their formation, they could hold molten material below the surface (for up to 6 Myr after CAIs; Sahijpal et al. 2007; Gupta & Sahijpal 2010), would be too small for significant rock-metal differentiation, and could retain an unmelted crust.

Quantitative modeling of glancing blows between molten planetesimals shows that an impact plume, originating primarily from the impactor, can be produced downrange of the collision (Asphaug et al. 2011). The model predicts the flow of the material and the size of droplets produced (Asphaug et al. 2011). Chondrule sizes in Isheyevo constrain the sizes of the impacting bodies to be in the tens of kilometers range (Asphaug et al. 2011). While it has been argued that some of the components in Isyehevo, such as the refractory inclusions and porphyritic chondrules, may have been incorporated from material in the nebula (Krot et al. 2008, 2009), such a scenario is inconsistent with our understanding of Solar System evolution, unless they originate as accretionary breccias of impact debris (Krot et al. 2014). As such, we propose that these particular components originate from a solid carapace (~5 km thick) on the impactor (Asphaug et al. 2011).

The results of quantitative modeling (Asphaug et al. 2011) show that material ejected from the impact will form a fan-like sheet. In the case consistent with components from Isheyevo, an ~500 km sheet of material is produced downrange a few hours post-collision (Asphaug et al. 2011). The ejecta includes clasts of material from the unmelted crust and material from the molten interior. Following impact, the ejecta plume will travel as a unit to a distance that is controlled primarily by the time it

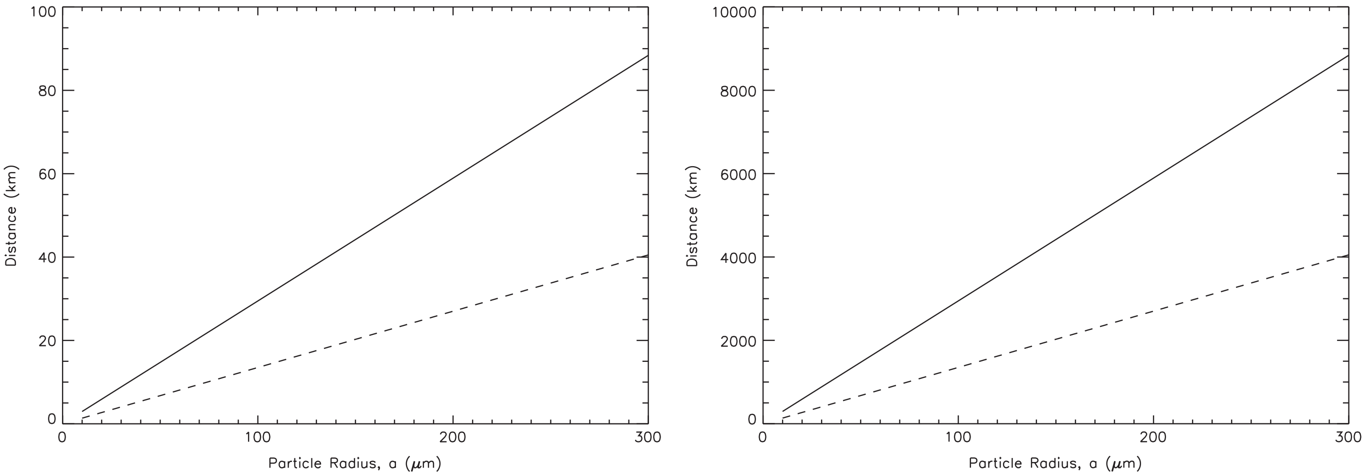

**Figure 2.** Left: distance traveled by metal and silicate spheres of varying radii, ejected from a common point at speed $V_0 = 30\ \mathrm{m\ s^{-1}}$, before being stopped by gas of density $\rho_g = 10^{-9}\ \mathrm{g\ cm^{-3}}$. Right: same as on the left, except the gas density is $\rho_g = 10^{-11}\ \mathrm{g\ cm^{-3}}$.

takes for the individual meteoritic components to condense. While the plume remains intact, it is large enough to be unaffected by the gas, so the distance traveled can be calculated based on the initial velocity $\sim V_{\mathrm{esc}} \sim 72\ \mathrm{m\ s^{-1}}$ (Asphaug et al. 2011). At this rate, the leading edge of the sheet of material will reach a distance that is comparable to the Hill radius ($r_{\mathrm{H}} = (M_{\mathrm{p}}/3\,M_{\odot})^{1/3}a \approx 2.1 \times 10^4$ km at 3 AU) in ~3.5 days. After components condense from the ejecta, the fan-like sheet will break apart due to Rayleigh–Taylor and Kelvin–Helmholtz instabilities, and will cease to move as a unit. Chondrules, zoned Fe, Ni-metal grains, unzoned metals, and clasts from the original crust of the projectile will then move independently until they are stopped by nebular gas according to their size and material density. The components are then swept up and reaccreted by the rotating surviving planetesimal downrange from the collision. This proposed reaccretion scenario requires the presence of nebular gas. However, the gas density at ~5 Myr is poorly constrained. It is also unclear when our Solar System went through its transitional stage, during which the amount of gas had decreased, but had not yet reached the level of a debris disk. We show that Isheyevo's sedimentary features provide insights into these questions.

### 3.1. *Aerodynamic Sorting of Ejecta*

Size sorting of materials in the ejecta occurs because components will travel varying distances before stopping. The stopping time before spherical droplets of different radii and density recouple to the gas is given by (Cuzzi et al. 2001)

$$t_s = \frac{\rho_s a_s}{c_s \rho_g}, \tag{1}$$

where $\rho_s$ is the particle density, $a_s$ is the particle radius, $c_s$ is the sound speed at 150 K, and $\rho_g$ is the gas density. For silicates, we use $\rho_s = 3.3\ \mathrm{g\ cm^{-3}}$ (representative of forsterite) and $\rho_s = 7.2\ \mathrm{g\ cm^{-3}}$ for Fe-rich metals. We consider a range of droplet sizes of 10–300 μm, typical of the sizes of chondrules and metal grains in chondrites. The distance traveled from a common point of origin by droplets of different radii and material density is given by $l_s \approx V_0 t_s$, where $V_0$ is the initial velocity of the droplet. In gas densities typical of the solar nebula at 2–3 AU at ~2 Myr ($\rho_g = 10^{-9}\ \mathrm{g\ cm^{-3}}$; Desch & Connolly 2002; Morris & Desch 2010; Desch et al. 2012), silicate spheres will travel ~1–40 km before recoupling to the gas, and metal spheres ~3–90 km, (Figure 2, left). The dependence of $l_s$ on $t_s$ results in sorting based on size and composition. Following the breakup of the impact plume, metal spheres will travel farther than silicates of similar size before their motions are arrested. In the case of lower gas density ($\rho_g = 10^{-11}\ \mathrm{g\ cm^{-3}}$), likely at 5 Myr (Figure 2, right), metal spherules will travel thousands of kilometers farther than similarly sized silicates. The difference in stopping times results in the aerodynamical sorting of the particles as shown in Figure 3.

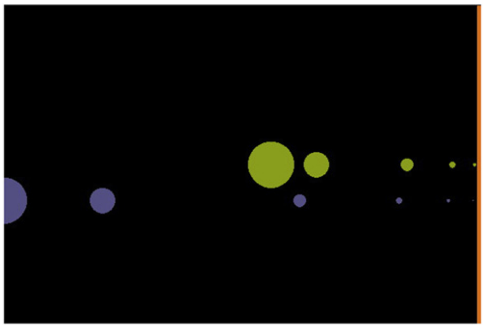

**Figure 3.** Distribution of silicate and metal spheres of different radii, originating from a common point, after becoming recoupled to the gas. Silicate spheres are shown in green and metal spheres are shown in blue. The Isheyevo parent body (indicated by the thin orange area) will sweep up particles as it travels from right to left.

After silicate and metal particles are stopped and recouple to the nebular gas, they must then reaccrete onto the Isheyevo parent body; otherwise, the components would disperse into the nebula. Previously proposed scenarios for reaccretion have invoked gravitational settling (Krot et al. 2008; Asphaug et al. 2011), but we argue that this process is too slow to present a reasonable method for reaccretion.

### 3.2. *Timescales for Gravitational Settling*

The gravitational settling time is given by $z/v_t$, where $z$ is the distance from the target, and the terminal velocity $v_t = g t_s$, where $g$ is the local gravity. In a nebula with $\rho_g = 10^{-11}\ \mathrm{g\ cm^{-3}}$, the time for silicate particles of 10–300 μm to settle from the

**Table 1**
Results of Parameter Study on Sweep-up Time

| $v_{\mathrm{su}}$ | $10^{-09}$ [a] | $10^{-10}$ | $10^{-11}$ | $10^{-12}$ | $10^{-13}$ |
|---|---|---|---|---|---|
| 25 m $s^{-1}$ | <1.0[b] | 0.3–10 | 3–98 | 33–982 | 327–9821 |
| 50 m $s^{-1}$ | <0.5 | 0.2–5 | 2–49 | 20–491 | 200–4910 |
| 100 m $s^{-1}$ | <0.2 | 0.08–2 | 0.8–24 | 8–245 | 80–2455 |
| 250 m $s^{-1}$ | <0.01 | 0.03–0.1 | 0.3–10 | 3–98 | 30–982 |
| 500 m $s^{-1}$ | <0.05 | 0.01–0.5 | 1–5 | 2–50 | 16–500 |

[a] Gas density in units of g $cm^{-3}$.
[b] Sweep-up in units of days.

Hill sphere of a planetesimal 70 km in diameter is 83–2500 yr. For similarly sized metal particles, the settling time is 38–1150 yr. Over such long time periods, particles will disperse through the nebula due to turbulence in the gas long before they are able to gravitationally settle to the body. Even were it possible for the particles to settle before dispersion, layering would not occur. As a consequence of the long timescales involved for gravitational settling, particles would reach terminal velocity long before nearing the body, reaching the surface simultaneously and erasing the effects of the size sorting. For higher gas densities, gravitational settling is even more improbable. For example, at $\rho_g = 10^{-9}$ g $cm^{-3}$, the time for particles to settle from the Hill sphere are two orders of magnitude higher than for $\rho_g = 10^{-11}$ g $cm^{-3}$. Therefore, reaccretion by gravitational settling is implausible.

### *3.3. Reaccretion Via "Sweep-up"*

Our calculations and data from Isheyevo are consistent with the rotating impacted body sweeping up material downrange of the collision, as it continues on with a slight velocity relative to the gas and particles. This sweep-up scenario is compatible with the size sorting of silicates and metals in Isheyevo. Our determination of the distribution of particles (Figure 3) predicts that chondrules will be swept up by the parent body with smaller-sized metals. In general, we observe that this is the case within Isheyevo. Size measurements from a representative piece of Isheyevo show that metals have a radius of 33 $\mu$m ($n = 161$) and silicates, including clay clasts, have a radius of 60 $\mu$m ($n = 56$). Sweep-up at low velocity is necessary to preserve the clay-rich clasts.

Our calculations suggest that sufficient mass can be swept up to produce meters-thick layers of particles resembling those found in Isheyevo. The fraction of particles swept up by a parent body with diameter $D \approx 70$ km will be $f = (\pi D^2)/(4A)$, where $A$ is the area of the fan-like sheet of material at the time it is reaccreted. If we assume the sheet of material stops moving as a unit after spreading to a distance $r \sim$ Hill radius $r_{\mathrm{H}} = (M_{\mathrm{p}}/3M_{\odot})^{1/3}\, a \approx 2.1 \times 10^4$ km, and assuming homologous expansion of a 500 × 500 km square at 3.3 hr, the sheet has area $\approx 2 \times 10^8$ $km^2$, so that $f \sim 2 \times 10^{-5}$. Gravitational focusing can increase this by a factor $\sim (v_{\mathrm{esc}}/2\,V)^2$, where $V \sim 1$ m $s^{-1}$ may reflect the random velocities of particles, yielding $f \sim 3 \times 10^{-2}$. In gas of density $\rho_g = 10^{-11}$ g $cm^{-3}$, and for an ejected mass $3 \times 10^{19}$ g (Asphaug et al. 2011), the mass of solids reaccreted is $\sim 8 \times 10^{17}$ g. This mass of solids is sufficient to coat the entire asteroid surface to a depth of about 1 m, or cover a fraction of the asteroid surface to greater depth, depending on its rotation rate. These preliminary calculations demonstrate that for the stopping lengths we consider typical, it is possible for the parent body to sweep up sufficient mass to produce the CH/CB/Isheyevo chondrites, provided the asteroid moves in the same direction as the ejecta, the initial velocity of the sheet of material, $V_0$, is low ($\sim V_{\mathrm{esc}}$), and the gas density is high enough to arrest the motions of the particles before they travel much farther than $\sim 2 \times 10^4$ km.

## 4. ASTROPHYSICAL IMPLICATIONS

Reaccreation by sweep-up at low velocity, while retaining evidence of the aerodynamic sorting, places constraints on the amount of turbulence in the nebula, as well as the density of the gas.

### *4.1. Turbulent Mixing Before Sweep-up*

In order to preserve the aerodynamic sorting effects of the particles, they must be swept up before they are mixed by turbulence. We have employed the methods described by (Cuzzi & Zahnle 2004) to determine the mixing timescale for individual components, once they have recoupled to the gas. The effective viscosity in a weakly turbulent nebula is given by $\nu_{\mathrm{t}} = \alpha c_s H$, where $\alpha$ is a dimensionless parameter determined by the mass accretion rate of the nebula, $c_s$ is the sound speed, and $H$ is the scale height of the disk. Both models and observations suggest that typically $\alpha \sim 10^{-5}$–$10^{-2}$ and $H \sim R/20$, where $R$ is the distance from the central star. The diffusivity due to turbulence is $D = \nu_{\mathrm{t}}/Pr_{\mathrm{t}}$, where $Pr_{\mathrm{t}}$ is the Prandtl number, typically assumed to be $Pr_{\mathrm{t}} = 1$, giving $D = \nu_{\mathrm{t}}$ (Cuzzi & Zahnle 2004). The timescale for mixing of particles separated by a distance $L$ is then $t_{\mathrm{mix}} = L^2/D$.

Assuming $\alpha = 10^{-5}$, and a maximum separation distance $L_{\max} \sim 8800$ km (as shown in Figure 2), $t_{\mathrm{mix}} \sim$ 100 hr. The largest components must be swept up within this time frame in order to preserve the sorting depicted in Figure 3. This requires that the Isheyevo parent body must move at a velocity $\geqslant$ 24 m $s^{-1}$ relative to the particles. This provides a lower limit to the relative velocity, $V_{\mathrm{rel}}$, we expect as a result of the collision. At minimum separation of $\sim$13 km, applicable to smaller particles, mixing can occur within one second. The average size of particles in Isheyevo indicates separation distances of $L\sim$ 6950 km, so $t_{\mathrm{mix}} \sim 70$ hr. This requires that the body move at $V_{\mathrm{rel}} \sim$ 28 m $s^{-1}$. An upper limit is provided by the preservation of the integrity, both thermally and mechanically, of the clay-like clasts. Therefore, it is likely that the sweep-up velocity falls at the lower limit of the range indicated by particle size. It is important to note that our calculations of the mixing timescale place constraints on the degree of turbulence in the disk, since for larger $\alpha$, $t_{\mathrm{mix}}$ is correspondingly shorter. We find that for $\alpha > 10^{-5}$, preservation of sorting, such as that observed in Isheyevo, is unlikely.

### *4.2. Gas Densities Needed to Meet Meteoritic Constraints*

Zoned Fe, Ni-metal grains, such as those found in Isheyevo, are interpreted to have formed and cooled in a matter of days to weeks, based on their chemical zoning profiles (Meibom et al. 2000; Petaev et al. 2001, p. 1657; Petaev & Jacobsen 2003 p. 1747; Campbell & Humayun 2004; Goldstein et al. 2007). This time constraint imposes bounds on the gas density of the PPD during their formation. Metal spheres formed in impacts and dispersed in gas at densities typical of the formation of most chondrules at around 2 Myr post CAIs ($\rho_g = 10^{-9}$ g cm$^{-3}$) would be stopped and reaccreated on timescales too short to allow for their condensation. Gas densities significantly lower than $\rho_g = 10^{-9}$ g cm$^{-3}$ would result in longer stopping times, causing dispersal of the impact products into the nebula, without reaccretion. In order to meet the constraints on cooling times for metal spheres, sweep-up must occur within days to weeks. According to our parameter studies (Table 1), gas densities in the range of $\rho_g = 10^{-11}$–$10^{-12}$ g cm$^{-3}$ are indicated for accreting bodies moving with a sweep-up velocity of $v_{\rm su}$ = 25–500 m s$^{-1}$.

## 5. CONCLUSION

Our calculations show that the components found in the Isheyevo meteorite are consistent with sweep-up at low velocity onto a pre-existing body, within nebular gas of density $\rho_g = 10^{-11}$–$10^{-12}$ g cm$^{-3}$. These densities are consistent with those of observed transition disks (Salyk et al. 2009; Williams & Cieza 2011). Through Isheyevo's association with meteorites that have components dated at around 5 Myr (Krot et al. 2005; Ivanova & Lorenz 2006; Bollard et al. 2013), we infer that this important stage in the evolution of the Solar System occurred at ~5 Myr. We also show that in order to preserve the observed sorting of Isheyevo components, sweep-up must occur in a turbulent disk with $\alpha < 10^{-5}$. Therefore, we conclude that Isheyevo, the oldest known sedimentary rock, accreted onto a pre-existing body in the Solar System's mildly turbulent transition disk, a heretofore purely theoretical phase in the primordial solar nebula.

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