Possible Implications of Relatively High Levels of Initial $^{60}$Fe in Iron Meteorites for the Noncarbonaceous–Carbonaceous Meteorite Dichotomy and Solar Nebula Formation

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Abstract

Cook et al. found that iron meteorites have an initial abundance ratio of the short-lived isotope $^{60}$Fe to the stable isotope $^{56}$Fe of $^{60}$Fe/$^{56}$Fe $\sim$ (6.4 $\pm$ 2.0) x 10$^{-7}$. This appears to require the injection of live $^{60}$Fe from a Type II supernova (SN II) into the presolar molecular cloud core, as the observed ratio is over a factor of 10 times higher than would be expected to be found in the ambient interstellar medium (ISM) as a result of galactic chemical evolution. The supernova triggering and injection scenario offers a ready explanation for an elevated initial $^{60}$Fe level, and in addition provides a physical mechanism for explaining the noncarbonaceous–carbonaceous (NC–CC) dichotomy of meteorites. The NC–CC scenario hypothesizes the solar nebula first accreted material that was enriched in supernova-derived nuclides, and then later accreted material depleted in supernova-derived nuclides. While the NC–CC dichotomy refers to stable nuclides, not short-lived isotopes like $^{60}$Fe, the SN II triggering hypothesis provides an explanation for the otherwise unexplained change in nuclides being accreted by the solar nebula. Three-dimensional hydrodynamical models of SN II shock-triggered collapse show that after triggering collapse of the presolar cloud core, the shock front sweeps away the local ISM while accelerating the resulting protostar/disk to a speed of several kilometers per second, sufficient for the protostar/disk system to encounter within $\sim$1 Myr the more distant regions of a giant molecular cloud complex that might be expected to have a depleted inventory of supernova-derived nuclides.

Unified Astronomy Thesaurus concepts: Planet formation (1241); Star formation (1569); Hydrodynamics (1963); Protoplanetary disks (1300); Supernova remnants (1667)

1. Introduction

Laboratory studies of the initial abundances of the short-lived isotope $^{60}$Fe (half-life of 2.62 Myr) have produced values differing by orders of magnitude. Tachibana et al. (2006) determined an initial ratio of $^{60}$Fe/$^{56}$Fe $\sim$ 5–10 x 10$^{-7}$ in their studies of high Fe/Ni ferromagnesian chondrules from the ordinary chondrites (OC) Semarkona and Bishunpur. Tang & Dauphas (2012) performed whole rock analyses of a range of meteorites, including unequilibrated ordinary chondrites (UOC), and found a much lower initial abundance ratio, $^{60}$Fe/$^{56}$Fe $\sim$ 1.15 x 10$^{-7}$, a level they considered to be representative of the general interstellar medium (ISM). However, when Mishra & Goswami (2014) examined seven chondrules from UOC meteorites, they found an initial ratio of $^{60}$Fe/$^{56}$Fe $\sim$ 7 x 10$^{-7}$. Mishra & Chaussond (2014) studied three chondrules from the OC Semarkona and the carbonaceous chondrite Efremovka, finding initial ratios of $^{60}$Fe/$^{56}$Fe in the range of $\sim$2–8 x 10$^{-7}$. Mishra et al. (2016) inferred ratios of $\sim$8–11 x 10$^{-7}$ for chondrules from an UOC, while Telus et al. (2018) found initial ratios in the range of $\sim$0.5–3 x 10$^{-7}$ in other UOC chondrules.

Telus et al. (2016) attributed the differences between whole rock analyses and in situ studies of individual chondrules to aqueous alteration along chondrule fracture lines, either on the parent body or prior to recovery on the Earth, which could skew the whole rock analyses toward lower initial $^{60}$Fe/$^{56}$Fe ratios. Trappitsch et al. (2018) reanalyzed a Semarkona chondrule with a different in situ technique, finding a low initial ratio of $^{60}$Fe/$^{56}$Fe $\sim$ (3.8 $\pm$ 6.9) x 10$^{-8}$ that is consistent with the low end of the range found by some other in situ analyses and with the low values found by the whole rock measurements of Tang & Dauphas (2012). The Trappitsch et al. (2018) results allow a solar system initial ratio as high as 1.07 x 10$^{-7}$.

The Tang & Dauphas (2012) result has been accepted by some as evidence of meteoritic $^{60}$Fe being the result of galactic chemical evolution (e.g., Forbes et al. 2021). Others have been more circumspect. Vescovi et al. (2018) simply concluded that the initial $^{60}$Fe/$^{56}$Fe ratio lies between 10$^{-8}$ and 10$^{-6}$, while Lugaro et al. (2018) decided that the initial $^{60}$Fe/$^{56}$Fe ratio has not been determined well enough to draw any conclusions about the source of this short-lived isotope. Given this checkered past, the Cook et al. (2021) study represents a potentially transformational approach to determining the initial $^{60}$Fe/$^{56}$Fe ratio. Rather than search for Fe–Ni-rich phases in the primarily silicate mineralogy of chondritic meteorites, Cook et al. (2021) analyzed 13 samples from two groups of magmatic iron meteorites, the common octahedrites (group ID) and the rare ataxites (group IVB), the former with average to high Ni contents, the latter with very high Ni. Magmatic iron meteorites offer the advantage of samples of a well-mixed iron melt, sidestepping the concerns about whole rock versus in situ measurements that characterize chondritic meteorites. The study was able to rule out contamination of the Fe and Ni isotopes by galactic cosmic-rays. Using the common assumption that the iron meteorites formed from the chondritic reservoir, Cook et al. (2021) found that an initial ratio of $^{60}$Fe/$^{56}$Fe $\sim$ (6.4 $\pm$ 2.0) x 10$^{-7}$ characterized their samples of these two groups of iron meteorites, a value considerably higher than expected as a result of galactic chemical evolution.
and thus provides meteoritical evidence in support of the supernova triggering and injection hypothesis that was first proposed by Cameron & Truran (1977). Lee et al. (1976) found evidence of live initial $^{26}\text{Al}$ (half-life of 0.72 Myr) in Ca, Al- rich refractory inclusions (CAIs) from the Allende meteorite, leading Cameron & Truran (1977) to hypothesize nucleosynthesis of $^{26}\text{Al}$ in an SN II and rapid incorporation of the $^{26}\text{Al}$ into CAIs following injection into the presolar cloud by the SN II shock wave. $^{26}\text{Al}$ is also synthesized during the Wolf–Rayet (W-R) phase of massive stars, prior to a core-collapse supernova explosion, and mixed into the interstellar medium by the W-R star outflow, and so the solar system level of $^{26}\text{Al}$ has been argued to be a result of GCE (e.g., Young 2016; Reiter 2020) or of triggering by a W-R outflow (Dwarkadas et al. 2017). However, $^{60}\text{Fe}$ is not produced in significant amounts by W-R stars, but as well as $^{26}\text{Al}$ is readily produced by SN II (e.g., Tur et al. 2010), making the initial $^{60}\text{Fe}$ abundance the key meteoritical test for an SN II being the primary source of the live $^{60}\text{Fe}$. Protosolar cosmic-rays have also been suggested as a source of $^{26}\text{Al}$ (most recently by Gaches et al. 2020) but such cosmic-rays fail to produce the required $^{60}\text{Fe}$.

A long series of papers, from Foster & Boss (1996) through to Boss (2019), has used detailed multidimensional hydrodynamics codes to show that suitable SN II shock waves are able to trigger the self-gravitational collapse of a molecular cloud core, while simultaneously injecting the short-lived isotopes into the collapsing cloud through the Rayleigh–Taylor instability at the shock-cloud boundary. These papers have proven the viability of the Cameron & Truran (1977) hypothesis for the origin of the short-lived isotopes inferred from meteoritical analyses such as those of Cook et al. (2021).

The purpose of this paper is to learn whether this series of shock-triggered-collapse models might have additional implications for explaining the noncarbonaceous–carbonaceous (NC–CC) dichotomy of meteorites. Warren (2011) was the first to show that meteoritical Cr, Ti, and O stable isotope abundances fall into two distinct groups, the NC and CC. Recent work by Nanne et al. (2019) and Lichtenberg et al. (2021) has developed models for creating and preserving the NC–CC dichotomy. Both scenarios hypothesize that the solar nebula first accreted material that was enriched in supernova-derived nucleides, and then later accreted material depleted in supernova-derived nucleides. No explanation is offered for a physical mechanism to explain this significant difference in accreted matter other than isotopic heterogeneity in the local ISM and an extended period of accretion from the ISM. Thus, we seek here to find a more dynamically based explanation for the NC–CC dichotomy. We extend the preferred triggered-collapse model of Boss (2019) to a much larger calculational volume and use it to track the evolution of matter initially in four distinct initial regions to learn the effect of shock wave triggering on the time evolution of matter accreted by the presolar cloud and nebula.

2. Numerical Hydrodynamics Code

The new model presented here was calculated in the same manner as the suite of shock-triggered collapse and injection models of Boss (2019). The three-dimensional hydrodynamics code used was once again FLASH 4.3, based on the algorithms developed by Fryxell et al. (2000). The FLASH codes are adaptive-mesh refinement (AMR) codes, ideal for following the sharp gradients in density and temperature associated with shock fronts as they traverse more uniformly varying regions of the ISM, such as molecular cloud cores. In addition to the AMR feature of FLASH, the models use a sink particle (as developed by Federrath et al. 2010) to represent the newly formed, high density protostar as a point source of gravity able to accrete matter from its surroundings. As in Boss (2019), the new model uses the FLASH 4.3 multigrid Poisson solver, and as a result uses a Cartesian coordinate grid with one top grid block with eight top grid cells in each coordinate direction. The model begins with a maximum of six levels of refinement on the top grid block. Because the computational volume is a rectangular cuboid with sides of length $4 \times 10^{17}$ cm in $\hat{x}$ and $\hat{z}$ and $1.12 \times 10^{18}$ cm in $\hat{y}$, the resulting cells are not cubical, being almost three times as long in the $\hat{y}$ direction as in $\hat{x}$ and $\hat{z}$. (Note that in Boss (2019), the rectangular cuboid had a significantly smaller length in $\hat{y}$ of $8.2 \times 10^{15}$ cm.) A single increase in the level of refinement means that each of the three sides of the computational cells are halved in length, leading to the increased spatial resolution that is needed to be able to accurately follow the dynamics of shock-triggered protostar collapse. With six levels of refinement, the smallest cell size in $\hat{x}$ and $\hat{z}$ is $4 \times 10^{17} / (2^6 \times 8) = 1.6 \times 10^{13}$ cm and a size 2.8 times larger in $\hat{y}$. When the refinement level is increased to seven, the smallest cell size is $0.8 \times 10^{15}$ cm in $\hat{x}$ and $\hat{z}$.

3. Initial Conditions

The model presented here is identical to one of the models (O) published in Boss (2019), with two exceptions. First, the length of the calculation box was extended in the direction of propagation of the shock front in order to learn more about the effect of the shock front on the ISM gas and dust downstream from the target molecular cloud core. Second, several new color fields were defined, in order to better define the fate of the surrounding ISM matter. The color fields are defined as being initially nonzero in specific regions of the initial configuration, such as inside the target cloud or inside the shock front, and these fields thereafter evolve and trace the location and density of this material as the calculation proceeds. The models in Boss (2019) focused on the material initially inside the shock front, in order to estimate the SN II injection efficiency, and did not specify color fields that tracked the material initially in the target cloud or the surrounding ISM. As a result, the Boss (2019) models could not separate the evolution of the initial target cloud material from that of the surrounding ambient ISM, which is the key goal of this paper.

As in Boss (2019), the initial conditions consist of a stationary target molecular cloud core that is about to be struck by a planar shock wave (Figure 1). The target cloud core and the surrounding gas are initially isothermal at 10 K, while the shock front and post-shock gas are isothermal at 1000 K. The target cloud consists of a spherical cloud core with a radius of 0.053 pc and a Bonnor–Ebert radial density profile. The central density is chosen to produce an initial cloud with a mass of $3.04M_\odot$, embedded in a background rectangular cuboid of...
gas with a mass of $1.63M_\odot$ and with random noise in the background density distribution. The cloud core is assumed to be in solid body rotation about the direction of propagation of the shock wave (the $\hat{y}$ direction) at an angular frequency $\Omega = 3 \times 10^{-14}$ rad s$^{-1}$. The initial shock wave has a speed of $40 \text{ km s}^{-1}$, a width of $3 \times 10^{-4}$ pc, and a density of $7.2 \times 10^{-18}$ g cm$^{-3}$. These choices are based on previous modeling, which examined a wide range of shock parameters (Boss et al. 2010; Boss & Keiser 2010), in order to choose shock parameters suitable for triggered collapse and injection of SN II derived short-lived isotopes.

4. Results

Figures 1–5 show the initial configuration and the four different color fields used to trace the evolution of different regions in the model. The first color field (denoted mass scalar 1 or ms1, in the FLASH code) depicts the matter in the target cloud, while ms2 traces the matter in the shock front, ms3 does the same for the matter behind the shock front, and ms4 follows the ambient ISM surrounding the target cloud core.

The time evolution of this model proceeds exactly the same as the corresponding model O in Boss (2019): the shock front...
smacks the top edge of the target cloud core, leading to a Rayleigh–Taylor instability at the shock-cloud interface. This instability allows shock front material carrying SN II-produced short-lived isotopes such as $^{60}\text{Fe}$ and $^{26}\text{Al}$ to be injected into the target cloud core, which is soon compressed sufficiently by the shock front to initiate sustained, self-gravitational collapse. Once the collapsing region exceeds a critical density of $10^{-15}$ g cm$^{-3}$ (0.048 Myr), a sink cell is formed at the location of the density maximum, and this sink cell thereafter accretes the gas and dust in its vicinity, using the same sink cell parameters as used in model O in Boss (2019). The model started with a maximum of six levels of refinement, which was increased to seven levels after 0.050 Myr of evolution. The portions of the shock that do not strike the target cloud exit off the calculational grid by 0.010 Myr.

Figures 6–10 depict the results for the density and four color fields at the final time calculated for the model of 0.063 Myr. This new AMR model required a run time of three months on
three 32-core nodes of the Carnegie memex cluster. At the final
time, the sink cell is located close to the center of the density
maximum evident in Figure 6 (at $y = -1.32 \times 10^{17}$ cm), has
been accelerated by the shock front to a speed of 3.2 km s$^{-1}$ in
the direction of the initial shock front, and has acquired a mass
of $\sim 0.5 M_{\odot}$. The protostar is accreting mass at a rate of
$\sim 10^{-6} M_{\odot}$ yr$^{-1}$, implying that it will grow to a final mass of
$\sim 1 M_{\odot}$ in $\sim 0.5$ Myr if that accretion rate could be sustained
indefinitely. However, at the final time, the mass accretion rate
is in decline, as the nearby gas and dust available for accretion
is being depleted.

Figure 7 shows that the initial cloud core has been only
partially triggered into self-gravitational collapse, with the
majority of the initial mass of $3.04 M_{\odot}$ having been accelerated
beyond the gravitational reach of the accreting protostar formed
by shock wave compression. Figure 8 indicates that, as in the
previous model O (Boss 2019), the shock front material has
been mixed into the same region occupied by the initial cloud

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Initial cross section ($z = 0$) of color field 2, representing the material initially within the shock front, plotted as in Figure 1. The shock is initially moving downward at 40 km $^{-1}$.}
\end{figure}
core gas and dust, leading to an injection efficiency into the collapsing protostar essentially the same as was previously determined, as discussed in detail in Boss (2017). Figure 9 shows that the low-density, hot post-shock gas follows right behind the shock front matter with only minimal mixing into the compressed region of high density gas and dust.

Figure 10 presents the key result of this simulation: the material initially in the immediate vicinity of the target cloud core has been quite efficiently swept away from the region of the protostar and of the material that it is still accreting. Only an insignificant amount of the initial ambient gas and dust remains close enough to the protostar to be accreted, less than 1/20 (by mass) compared to the shock front matter at densities above $2 \times 10^{-16}$ g cm$^{-3}$. The model shows that SN II derived isotopes will be injected thereafter, with only minimal subsequent accretion of isotopes from the initial ambient ISM in the immediate vicinity of the target molecular cloud core, which is assumed to be initially pristine and unpolluted by SN
II shock ejecta. This sweeping away of the local ISM allows the protostar to experience two distinct phases of accretion, first due to SN II shock injection, and later during its subsequent traverse of the giant molecular cloud (GMC). Figures 11 and 12 provide close-up views of the model at the final evolution time, showing the newly formed protostar/protoplanet disk surrounding the location of the protostar (i.e., sink cell). Figure 12 shows that only faint wisps of the initial ambient ISM material still remain in the region of the protostar. Figure 13 shows that the shock wave isotopes have been injected deep within the protostar and disk system, as a result of the Rayleigh–Taylor fingers that pierce the target cloud core early in the evolution. Finally, Figure 14 depicts the temperature distribution at the final time, showing that the protostar is located well behind the high temperature (1000 K) shocked region and retains its initial temperature of 10 K as a result of molecular line cooling in
optically thin regions (Boss et al. 2008). The protostar thereafter continues its evolution into the GMC with its ambient temperature of 10 K.

Figure 11 superficially resembles Figure 5 of Boss (2019), which depicts the results of a model (N) with an initial cloud rotation rate 2/3 of that in the current model, based on model O and shown in Figure 6 of Boss (2019). In Boss (2019), model O produced a large-scale disk by 0.121 Myr, with a diameter of order 1000 au, whereas model N did not produce a large-scale disk by the time that the model was halted, 0.081 Myr. The present model shown in Figure 11 was halted at 0.063 Myr, even earlier than model N in Boss (2019), as the result of an increasingly smaller time step problem that did not afflict model O in Boss (2019). As the present model is identical to model O, save for the extension of the numerical grid from $y = -2 \times 10^{17}$ to $y = -5 \times 10^{17}$ cm effected in order to better study the fate of the surrounding ISM matter, one must ascribe this small time step problem to the computational cells being increasingly elongated in $\hat{y}$ that had to be employed in order to use the improved multigrid Poisson solver of FLASH 4.3, as

Figure 6. Final log density cross section ($z = 0$) after 0.063 Myr with seven levels of refinement. By this time, the portions of the shock front that did not strike the target cloud have exited the bottom of the grid.
explained by Boss (2019). Hence, one can expect that the present model would produce a large-scale disk identical to that of model O if the model could be calculated as far as model O in Figure 6 of Boss (2019), i.e., to 0.121 Myr. A careful examination of the present model in Figure 11 shows that a disk is beginning to form, as there are distinct horns of accreting matter both above and below the location of the central protostar, with the horns above the protostar being clearly bent outward compared to those of model N in Figure 5 of Boss (2019), indicative of the higher initial rotation rate of the present model compared to model N and of the subsequent disk formation in model O. Regardless of the small time step problem, the present model’s extension in $\hat{y}$ allows Figure 10 to demonstrate that the shock front effectively clears away the residual ISM matter from the vicinity of the protostar and disk system, a fact that cannot be gleaned from model O’s Figure 6 in Boss (2019), where the disk system is about to reach the end of the numerical grid.

The mass of the initial shock front is $0.50M_\odot$ and it is traveling at a speed of 40 km s$^{-1}$, giving it a total momentum...
of $20M_e$ km s$^{-1}$. At the final time, the protostar has a mass of $\approx 0.5M_e$ and has been accelerated to 3.2 km s$^{-1}$ in the direction of the initial shock front, giving it a total momentum of $\approx 1.6M_e$ km s$^{-1}$. Thus the protostar has acquired less than $1/10$ of the total initial momentum of the shock front. At the rate of 3.2 km s$^{-1}$, the protostar/disk system will traverse $\sim 3$ pc through the background GMC complex in 1 Myr, accreting gas and dust from other, more distant regions of the GMC that have not been polluted recently by an SN II explosion. Given that GMC diameters range from $\sim 5$ to $\sim 200$ pc, there would appear to be an adequate GMC volume for a protostar launched at $\sim 3$ km s$^{-1}$ to scatter off other protostars in the GMC star-forming regions and accrete further ISM material and non-SN II derived isotopes.

5. Implications for the NC–CC Dichotomy

By this time, the implications of this model should be clear: they provide a physically reasonable explanation for the NC–CC dichotomy, as advanced by (Nanne et al. 2019, see their
These authors hypothesized that the solar nebula initially accreted material that was enriched in SN II derived isotopes, and some time later accreted material depleted in SN II derived isotopes.

While no timescale for these two accretion phases is presented by either Nanne et al. (2019) or Lichtenberg et al. (2021) other than the phrases early infall and late infall, the present model suggests that the early infall phase lasted for $\sim 0.1$ Myr, based on the final model time reached, while the late infall phase lasted for $\sim 1$ Myr, based on the speed of the protostar and GMC sizes. These suggestions are supported by the work on the NC–CC dichotomy by Kruijer et al. (2020), whose Figure 5 explicitly states that the early infall occurs at $t = 0$ Myr, implying a timescale much less than 1 Myr, along with assuming the simultaneous formation of CAIs, while late infall stops by 1 Myr, when Jupiter is supposed to have formed and prohibited mixing of the inner NC and outer CC reservoirs.

Isotopic heterogeneity throughout the GMC where the solar system was formed is required, but the present model

Figure 9. Final cross section ($z = 0$) of color field 3, representing the material initially behind the shock front, plotted as in Figure 6.
provides a physical reason for the change in the SN II derived isotopic composition of the matter being accreted by the protosun and solar nebula. Jacquet et al. (2019) make a similar argument for isotopic heterogeneity in the matter accreted by the solar nebula without specifying a physical mechanism to explain the origin of the heterogeneity. Others have argued that physicochemical processing of dust grains could be a better explanation for certain isotopic anomalies ($^{150}$Nd) than heterogeneous infall (Saji et al. 2021).

Hopp et al. (2022) have argued that Fe isotopic abundances in iron meteorites reflect the same NC–CC dichotomy as other meteorites. They conclude that the Fe isotope dichotomy can be explained by nuclear statistical equilibrium in either type Ia SN or in core-collapse SN, i.e., SN II.

Ideally the present calculation could be extended indefinitely further in time to capture both the early infall and late infall phases advanced by Nanne et al. (2019) and Lichtenberg et al. (2021). This is not possible for the present model for two
reasons. First, increasingly smaller time steps are required to push the calculation any farther in time than the 0.063 Myr shown in Figures 6–12, effectively halting this particular model. Second, even without the time step problem, the protostar and disk system seen in Figure 12 at $y = -1.3 \times 10^{17}$ cm would reach the end of the computational volume at $y = -5 \times 10^{17}$ cm within about another 0.038 Myr, traveling at 3.2 km s$^{-1}$, too quickly to transition to the late infall phase. Note that prior to reaching the bottom of the computational volume, the dense gas that is accreting onto the central system (orange-red colors in Figure 12) will have been accreted, as the freefall time for collapse at a gas density of $10^{-16}$ g cm$^{-3}$ is 0.0067 Myr, effectively ending the early infall phase.

If the present scenario is deemed interesting, future work would be needed to consider a more global model of an entire GMC struck by an SN II shock wave that follows the progression of the resulting shock-triggered protostar(s) as they traverse the GMC. In lieu of such an ambitious three-dimensional hydrodynamics model, we can predict the mass accretion rate that should characterize the late infall phase. The protostar will accrete gas from the region of the GMC it traverses at a rate that can be calculated by the Bondi–Hoyle–

Figure 11. Close-up view of the final log density cross section $(z = 0)$ after 0.063 Myr as seen in Figure 6. The sink cell is located in the center of the density maximum and represents the newly formed protostar and disk system.
Lyttleton (BHL) formula given by Ruffert & Arnett (1994): 
\[ \dot{M}_{\text{BHL}} = \pi R_A^2 \rho_A v_A, \]
where the accretion radius \( R_A \) is given by 
\[ R_A = \frac{2GM}{\rho_A v_A^2}, \]
with \( G \) being the gravitational constant, \( \rho_A \) being the ambient GMC gas density, and \( v_A \) is the speed of the protostar with respect to the ambient gas. With an ambient GMC gas density of \( \rho_A = 10^{-21} \text{ g cm}^{-3} \), typical of GMC average densities and the same as the background gas in the present model (see Figure 1), \( v_A = 3.2 \text{ km s}^{-1} \), and a protostar and disk system mass of 1\( M_\odot \), we obtain a mass accretion rate of \( \dot{M}_{\text{BHL}} = 10^{-4} M_\odot \text{ Myr}^{-1} \) of ambient GMC gas and dust. If the protostar system should pass through a dense molecular cloud core with a mean density of \( \sim 10^{-19} \text{ g cm}^{-3} \), as assumed in the present model (Figure 1), then the mass accretion rate would increase to \( \dot{M}_{\text{BHL}} \approx 10^{-2} M_\odot \text{ Myr}^{-1} \) while traversing the molecular cloud core, which would take about 0.03 Myr at 3.2 km s\(^{-1}\). These estimates suggest that the mass of pre-existing GMC gas and dust that has not been enriched by the triggering SN II shock wave that would accreted by the protostar during a late infall phase lasting \( \sim 1 \text{ Myr} \) would be in the range of \( 10^{-4} M_\odot \) to \( 3 \times 10^{-4} M_\odot \) of dense cloud core gas and dust. If the late infall phase lasts longer than 1 Myr, given that a protostar moving at 3.2 km s\(^{-1}\) travels 3 pc in 1 Myr, but GMCs can span \( \sim 5 \) to \( \sim 200 \) pc in size, the protostar could continue to accrete ambient GMC matter for longer than 1 Myr. Either way, the total accreted mass in the late infall phase is likely to be of order \( 10^{-4} \) to \( \sim 3 \times 10^{-4} M_\odot \).

**Figure 12.** Close-up view of the final cross section \((z = 0)\) of color field 4, representing the material initially outside the target cloud core, plotted as in Figure 11.
What are the implications of these estimates for the masses of the CC and NC component? Given that model O in Boss (2019), the model recalculated here with a longer computational volume, produced a disk with an initial mass of 0.05 \( M_\odot \), representing the early infall or CC component, whereas the late infall or NC component mass accretion estimate is in the range of \( 10^{-4} \) to \( \sim 3 \times 10^{-4} M_\odot \), this implies that the CC component was about 170–500 times as massive as the NC component. While specific values for the masses of the early infall enriched matter and late infall depleted matter are not given by Nanne et al. (2019), Lichtenberg et al. (2021) suggest that their Reservoir I (NC) had a total mass of about a Earth mass of planetesimals, while their Reservoir II (CC) had about a Jupiter mass of planetesimals, implying that the early infall CC matter was about 318 times as massive as the late infall NC matter. Given the uncertainties involved in both the present model and the Lichtenberg et al. (2021) estimates, having these two estimates agree to within a factor of 2 is remarkable and suggests that the scenario proposed herein is worthy of further scrutiny.

6. Conclusions

Observations of star-forming regions have demonstrated that star formation can be triggered by supernova explosions (e.g., Bialy et al. 2021). The meteoritical evidence discussed in this paper, coupled with the results of the new model presented
here, along with the previous papers in this series, appear to provide a reasonable argument that the solar system was formed as a result of the interaction of an SN II shock wave with a dense molecular cloud core residing within a GMC complex.

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References
Bialy, S., Zucker, C., Goodman, A., et al. 2021, ApJL, 919, L5
Boss, A. P. 2017, ApJ, 844, 113
Boss, A. P. 2019, ApJ, 870, 3
Boss, A. P., Ipatov, S. I., Keiser, S. A., Myhill, E. A., & Vanhala, H. A. T. 2008, ApL., 686, L119

Figure 14. Close-up view of the final cross section (z = 0) of the log temperature distribution, plotted as in Figure 11.

\[
\text{time} = \ 0.063 \ \text{klyr} \\
\text{number of blocks} = \ 20385, \ \text{AMR levels} = \ 7
\]
