THE SUPERNOVA TRIGGER REVISITED. A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics.

A number of years ago Jim Truran and I [1] proposed, primarily as a mechanism for bringing short-lived radioactivities and other isotopic anomalies into the solar nebula, that the collapse of a molecular cloud core to form the solar nebula was triggered by the arrival of a shock wave generated by the explosion of a supernova a few parsecs away. The idea was premature as the observational and theoretical data needed for its analysis was not yet present in sufficient detail. More recently [2], a small consortium of us revived the supernova trigger based on theoretical yields from massive supernovas and on meteoritic data; we estimated that shock velocities of 10 to 25 km/sec would suffice to do the job if supernovas of initial masses 25 to 60 $M_{\odot}$ exploded at 2 to 10 parsecs from the parental nebular cloud core. The needed efficiency for incorporating incident material into the collapsing core was estimated to be a few tens of percent. In the current presentation a more detailed discussion of the triggering event is given. Smooth particle hydrodynamic simulations are under way here and conventional hydrodynamic simulations are being carried out by Boss and colleagues [3].

Actually, there are a number of stellar sources that can produce some extinct radioactivities and that can produce shock waves strong enough to initiate core collapses. We restrict our attention to sources of radioactivities that are so short-lived that there is a fair chance they can be transported from the source to a molecular cloud core without too much decay. Novas can produce lots of ^{26}Al during the high temperature surface hydrogen burning that accompanies their eruptions, but the production of the other extinct radioactivities at higher charge numbers is greatly inhibited. AGB stars end their lives by ejecting a planetary nebula that can contain products of hydrogen and helium burning. Of the five shortest-lived extinct radioactivities, they can supply ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{60}Fe, but they cannot supply ^{53}Mn. Core implosion supernovas (Types Ib, Ic, and II) can supply all five of the shortest-lived and lightest extinct radioactivities, and they can make large quantities of these nuclides. This is the scenario that will be discussed here. It should also be noted that strong ultraviolet emission from massive stars can accelerate clouds to have 10–20 km/sec collisions with neighboring clouds, which may trigger core collapse without fresh radioactivities being included.

First, what is the cloud core like before impact by such a shock wave? Regions of density enhancement can be magnetically supported for long periods of time against dynamic collapse. Here the rate of contraction is governed by ambipolar diffusion, the slipping of neutral atoms and molecules across the magnetic field lines at a rate controlled by the collisions of ions and neutrals. The process has been extensively discussed by Mouschovias [4]. By his analysis, the initial formation of molecular cloud cores takes place entirely under the control of ambipolar diffusion. The core contracts steadily, with the rate remaining under magnetic control, until the central density reaches $\sim 10^9$ particles/cm^3. In the later stages of this quasistatic contraction, the magnetic flux loss time scale remains greater than the free fall time scale by a factor of 3–5. During this contraction the density increases more slowly than in free fall by about an order of magnitude (thus even with diffusion the magnetic flux suffers compression). I give here a simple analysis in which the core is represented by a uniform density sphere.

If this sphere starts collapsing from rest, then the free fall time is $t_{ff} = (3\pi/32G\rho)^{1/2}$.

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Here G is the gravitational constant and ρ is the initial density from which the collapse starts. For example, if $\rho = 10^{-21}$ gm/cm^3, then the free fall collapse time is 2.1×10^6 years. Note that free fall collapse occurs in the absence of any supporting internal pressure that would act to retard the gravitational acceleration. The above density is a typical molecular cloud density that one would likely have surrounding a core. If the core starts out very dense, say $\rho = 10^{-18}$ gm/cm^3, then t_{ff} is 6.6×10^4 years for the bulk of the core collapsing at this mean density. However, if the core starts out very nearly in pressure equilibrium, then the net inward force that would tend to induce collapse is just a small fraction of the total gravitational force, and the early part of the collapse would be stretched out in time by a large factor. Most of the entire free fall collapse time is spent near the initial configuration, so it is this early part of the collapse that is greatly lengthened in time. The critical reference time scale for contraction/collapse is the mean life of ^{41}Ca, or just 1.5×10^5 years. It may be seen that a realistic collapse will take very many mean lives of ^{41}Ca, and therefore an unassisted collapse time scale is inconsistent with finding this nuclide in the solar nebula.

I use a virial theorem approach to determine the stability against collapse of a cloud core. The virial theorem involves the sum of several energy terms.

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2K + 3(\gamma - 1)U + \mathfrak{M} + \Omega - 3P_{\text{ext}}V$$

Here I is the moment of inertia. The second derivative of this (and the right hand side of the equation) must be negative for collapse. K is the macroscopic kinetic energy of the system. It will in general include all dynamic motions such as collapse, rotation, and turbulence. We wish to apply it in conditions where collapse motions are small, where magnetic connectivity has removed most of the rotation, and we have no large-scale turbulence, so this term will be neglected. γ is the ratio of specific heats and U is the internal thermal energy. $\mathfrak{M}$ is the total magnetic energy of the system. Ω is the gravitational potential energy. P_{ext} is the external pressure exerted on the surface bounding the volume V. The negative terms that promote collapse are the gravitational potential energy Ω and the term involving the external pressure.

Consider now assisted star formation. The last term in the above equation, $-3P_{\text{ext}}V$, can provide this assistance. If this term becomes numerically large, then the second derivative of the moment of inertia, I, turns very negative, and the cloud core can be rapidly crushed to higher densities at which the residual free fall times become very short. This can be accomplished by shock waves. However, beware that if the cloud core is handled too roughly, it can be shattered into many pieces. Shock velocities of at least a few km/sec and up are therefore of potential interest in inducing star formation when they interact with existing molecular cloud cores. Some numerical examples will be given of the application of this concept to the triggering process.

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References: [1] Cameron, A. G. W. and Truran, J. W. [1977] *Icarus*, **30**, 447–461; [2] Cameron, A. G. W., Höfflich, P., Myers, P. C., and Clayton, D. D. [1995] *Astrophys. J.*, **447**, L53–L57; [3] Boss, A. P. [1995] *Astrophys. J.*, **439**, 224–236; [4] Mouscovias, T. C. [1991] *Astrophys. J.*, **373**, 169–186.

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