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The Origin of Chondrules at Jovian Resonances

S. J. Weidenschilling *et al.*

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cited electrons through attractive Coulomb interaction. The spatial localization of these excited electrons reduces their probability for scattering with other electrons, resulting in longer lifetimes as compared with nonlocalized excited electrons. Just as in our experiment, in which structural modification was exclusively induced by the interband transition exciting green light, this long-lived electronic state is absent when intraband transitions by IR light are excited (*15*). We suggest that this long-lived excited electronic state induces a Jahn-Teller–like configurational distortion.

This long-lived electronic state cannot, however, be the only driving force. For an exclusively electronic origin, the rate of adatom and vacancy production should simply be proportional to the number of initially excited electrons, which in turn is proportional to the photon fluence (*16*), because nonlinear optical effects are excluded (*17*) in the fluence range covered by our experiment. We observed, however, that the production rate depended nonlinearly on fluence and, moreover, that it was enhanced at higher static sample temperatures. These findings suggest that phononic excitation also plays a role. Simultaneous adatom and vacancy production is characterized by an activation energy barrier (*8*), the height of which depends on the instantaneous configuration of the surrounding atoms. The probability that the minimal activation energy configuration is met increases with phononic excitation produced by static temperature and transient temperature rise. Thus, in this proposed picture, the concerted action of electronic and phononic driving forces leads to localization of energy and ultimately to the formation of an adatom-vacancy pair.

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The Origin of Chondrules at Jovian Resonances

S. J. Weidenschilling,* F. Marzari, L. L. Hood

Isotopic dating indicates that chondrules were produced a few million years after the solar nebula formed. This timing is incompatible with dynamical lifetimes of small particles in the nebula and short time scales for the formation of planetesimals. Temporal and dynamical constraints can be reconciled if chondrules were produced by heating of debris from disrupted first-generation planetesimals. Jovian resonances can excite planetesimal eccentricities enough to cause collisional disruption and melting of dust by bow shocks in the nebular gas. The ages of chondrules may indicate the times of Jupiter's formation and dissipation of gas from the asteroidal region.

Chondrules are millimeter-scale igneous silicate spherules that constitute as much as half of the mass of chondrites, the most common type of meteorite. Many sources for chondrules have been proposed (*1*), but there are problems with each mechanism (*2*). The preponderance of opinion (though far from unanimous) is that they were produced by transient heating events that melted primitive aggregates of dust within the solar nebula (*3*, *4*). Individual meteorites differ in mean compositions and sizes of their chondrules, implying that they were not mixed extensively in the solar nebula, but accreted into planetesimals soon after they solidified (*5*). However, many chondrules show evidence of multiple heating episodes, suggesting that heating events were localized and frequent (*6*).

The oldest components of chondrites are Ca-Al–rich inclusions (CAIs), millimeter- to centimeter-sized objects composed of refractory minerals. CAIs appear to have been exposed to high temperatures, possibly during the infall phase that formed the sun and the solar nebula (*7*). Some CAIs show evidence of in situ decay of ^{26}Al (half-life = 0.73 million years); those that lack such evidence appear to have been reprocessed (*8*). Unaltered and reprocessed CAIs can be found within the same meteorite, implying that alteration occurred before accretion. In contrast, few chondrules containing Al-bearing minerals show evidence for the presence of ^{26}Al at the time they solidified, implying that they formed a few million years later, after the ^{26}Al decayed (*9*).

Wood (*5*) suggested that chondrules were produced during the collapse that formed the solar nebula from the presolar cloud or during the accretion disk phase that redistributed the nebula's mass and angular momentum because more energy was released during these events than in the later, relatively quiescent nebula. Proposed early energy sources include infall of interstellar grain aggregates through an accretion shock (*10*); shock waves due to clumps of interstellar gas falling onto the disk (*11*); density waves in the disk (*12*); and outflows, jets, or flares from the early sun (*13*–*15*). The CAI-chondrule age difference, if real, argues against these mechanisms, which would have been effective during the first million years or less of the nebula's evolution. There have been numerous suggestions that chondrules were melted by shock waves in the nebula (*11*, *12*, *16*), but most mechanisms proposed for producing shock waves occur at the wrong time (too early to explain the CAI-chondrule age difference) or place (far from the nebula's central plane, or much closer to the sun than the present asteroid belt), or both.

It is generally assumed that CAIs and chondrules were produced before planetes-

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*To whom correspondence should be addressed. E-mail: sjw@psi.edu imals accreted. However, if CAIs remained as isolated objects in the solar nebula, gas drag would have caused them to spiral into the sun on a time scale of only 10^5 years (*17*). Whereas some models of chondrule formation suggest that CAIs were stored as individual objects (*18*), most either ignore the problem of dynamical lifetimes or assume that the isotopic data represent nebular inhomogeneities rather than actual ages (*12*). Simulations of planetesimal formation show that bodies large enough to be preserved from loss by gas drag (diameter >1 km) could accrete on time scales of $\sim 10^3$ orbital periods (*19*), only $\sim 10^4$ years after the nebula had cooled enough to allow condensation of silicates in the asteroid region. Thus, CAIs could have been stored within a first generation of planetesimals. These had to be broken up at the time that chondrules were produced, then reaccreted. Production of chondrules from debris of disrupted planetesimals has been suggested on the basis of textures and mineralogy (*20*), and is consistent with shock features due to high-velocity impacts in some CAIs and chondrules (*21*), and relict grains, interpreted as recycled chondrule fragments, found within some chondrules (*22*). One objection to this idea has been the contradictory requirements for high-speed impacts to break up the primary planetesimals and low velocities to allow accretion of second-generation planetesimals. We suggest a dynamically plausible explanation of this paradox: Jupiter, which consists largely of H and He, must have formed before the nebula gas dissipated. Therefore, gas may have remained in the asteroidal region for some time after Jupiter attained its final mass. During that interval, this zone was subject simultaneously to jovian gravitational perturbations and damping by gas drag; these circumstances resulted in collisional breakup of planetesimals, heating of their fragments to produce chondrules, and reaccretion.

Hood (*23*) proposed that large planetesimals had orbits that were eccentric or inclined, or both, and supersonic velocities relative to the nebular gas. Small silicate particles entrained in the gas could be melted by passage through bow shocks of such bodies. For expected nebular densities, millimeter-sized particles are most easily melted (*24*). Hood suggested planetesimals were accelerated by gravitational perturbations by the forming outer planets, primarily Jupiter. Possible mechanisms for stirring velocities include close encounters with planets and long-range resonant interactions. The former is unlikely because Jupiter-crossing bodies would quickly be ejected from the solar system on hyperbolic orbits (*25*). Before ejection, they would traverse a large volume of space interior and exterior to Jupiter's orbit, with inclinations that would take them far from the nebula's central plane, where small particles would settle. Chondrule production by such bodies would, therefore, be inefficient. There is also no obvious source of particles for chondrule precursors after most of the available solids accreted into large planetesimals. We show that orbital resonances with Jupiter are a plausible source of high-speed planetesimals within the asteroid zone.

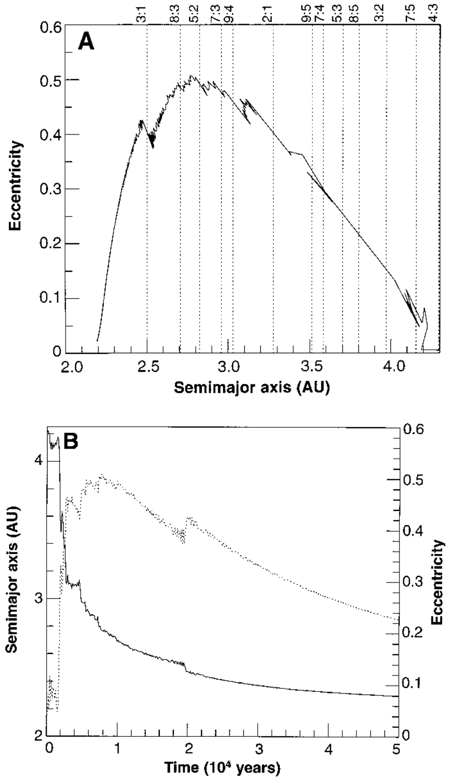

Fig. 1. (**A**) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started at 4.2 AU. Dashed lines mark the centers of major commensurability resonances, which overlap at eccentricities above 0.2 to 0.3 (*27*). (**B**) Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). Migration from 4.2 to 2.5 AU takes about 40,000 years; eccentricity exceeds 0.3 for most of this interval.

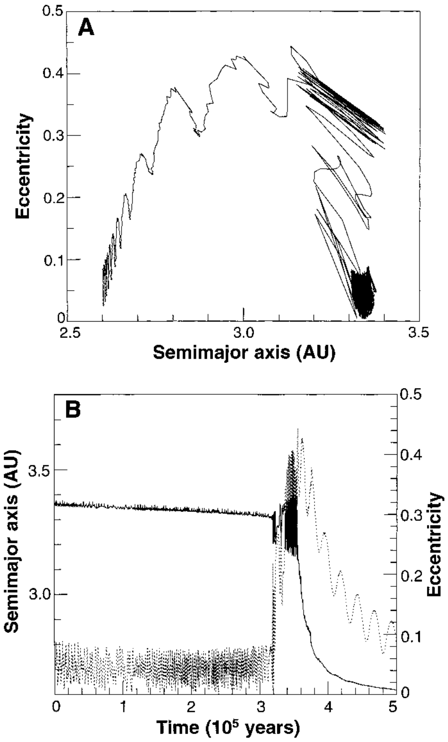

Fig. 2. (**A**) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started outside the 2:1 resonance. Jupiter is assumed to have its present eccentricity of 0.048. The planetesimal becomes trapped in the resonance until its eccentricity exceeds 0.3, then it escapes and is damped by drag. (**B**) Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). There is 3×10^5 years of slow orbital decay before encountering the resonance. Eccentricity increases rapidly while the planetesimal is trapped and remains above 0.3 for about 40,000 years.

At a commensurability resonance, the orbital periods of a planetesimal and planet are a ratio of small integers. The planet's gravitational perturbations are exerted repeatedly with the same geometry, maximizing their effect. The strongest jovian resonances within the asteroid region are the 3:2 and 2:1, at semimajor axes (mean distances) near 3.97 and 3.28 astronomical units (AU). We integrated orbits of asteroid-sized (diameters of 20 to 100 km) planetesimals perturbed by Jupiter and subject to nebular gas drag (*26*), and identified two mechanisms by which resonances can produce velocities high enough to melt chondrule precursors in bow shocks. The first applies to a planetesimal originating outside the 3:2 resonance. Gas drag causes its orbit to decay until it reaches the resonance, where jovian perturbations increase its eccentricity. If its eccentricity becomes large enough during passage through the 3:2 resonance, other higher order resonances overlap (*27*) and can raise it further. The combination of resonant perturbations and gas drag causes a rapid decrease in semimajor axis, driving it through multiple resonances without encountering Jupiter (Fig. 1). This mechanism is effective whether Jupiter's orbit is assumed to be circular or eccentric.

The second mechanism requires an eccentric jovian orbit, and involves passage through the 2:1 resonance. Bodies brought into this resonance by drag reach eccentricities of at least 0.1 during resonance passage. However, if Jupiter has a nonzero eccentricity (its present value is 0.048), a planetesimal may become temporarily trapped in the resonance. Its eccentricity can be increased significantly before it escapes from the resonance (Fig. 2).

Either mechanism can raise eccentricities of asteroid-sized bodies to at least 0.3, despite damping by gas drag. This eccentricity corresponds to a maximum velocity ≈5 km s^{-1} relative to the gas, which is ample to produce shock heating and melting of chondrules. The region affected is about 2.5 to 3.5 AU from the sun (because the motion of the gas is nearly Keplerian, a planetesimal's maximum velocity relative to the gas occurs near its mean orbital radius; it is about half as large near perihelion and aphelion). At high eccentricities, the rate of orbital decay is much greater than for a comparable body in a circular orbit (*28*). Each body spends only a short time at high velocities—a few times 10^4 years for a planetesimal 100 km in diameter. However, this process would be repeated until the supply of planetesimals was exhausted or the nebular gas dissipated, possibly for millions of years (*29*).

Planetesimals in resonances attain high eccentricities while their inclinations remain low (*30*). Their nearly coplanar orbits produce a high probability of collisions, which would yield abundant dust near the nebula's central plane. Some material melted by bow shocks would be immediately accreted by resonant bodies. However, because a shock is strong to at least twice the planetesimal's radius (*23*), most would be heated in passing by close encounters. Some particles would have repeated passages through bow shocks, consistent with evidence for multiple heating episodes (*6*). Chondrule production is more efficient than estimated by Hood (*23*) because of the low inclinations of resonant planetesimals. For a rough estimate, we assumed that their mean inclination is 0.5° and the dust is in a layer of similar thickness. The volume of this layer between 2.5 and 3.5 AU is $\sim 3 \times 10^{39}$ cm^3 . If a bow shock has twice the planetesimal's diameter, a 100-km body that spends 40,000 years in resonance moving at 5 km s^{-1} sweeps out 2×10^{32} cm^3. One Earth mass of such bodies (6×10^6 objects) would sweep out 40% of the dust layer's volume. Thus, a significant fraction of the dust could be processed by shocks. Chondrules, dust, and unmelted debris (including CAIs) would settle and drift inward because of gas drag. This material could accrete into second-generation planetesimals or be accreted onto the surfaces of first-generation planetesimals, or both; accretion onto first-generation planetesimals would allow concentration of chondrules by aerodynamic sorting (*31*). High-speed collisional disruption and low-speed accretion could occur simultaneously because gas would damp velocities of small particles and nonresonant planetesimals.

Resonance stirring is stochastic; the eccentricity produced by resonance passage and the probability of trapping in resonance depend on a planetesimal's angular separation from Jupiter as it approaches the resonance (*32*). Test bodies started just outside the 3:2 resonance had about equal probability of being scattered by Jupiter, damped to low eccentricity after passing through the resonance, or stirred to high velocities by multiple resonances. For bodies started just outside the 2:1 resonance, about 15% were stirred to eccentricities greater than 0.3. These proportions appear to be similar for all planetesimals with diameters greater than ~20 km. Differences in composition, sizes, and abundances of chondrules among various meteorites may be due to the stochastic nature of the chondrule-forming process. The abundance of dust would vary with time, depending on the frequency of collisions; its composition might also be dominated by the contribution of a small number of bodies involved in the most recent large collisions. The probability of heating would also depend on the number of large planetesimals in resonance at a given time. Multiple resonance passage can transport asteroids from the outer part of the belt to its inner region and may have contributed to radial mixing of compositional types (*33*).

If chondrules were produced before planetesimals accreted, then all planetesimals would have incorporated a significant proportion of chondritic matter. This reasoning leads to estimates that an amount of matter exceeding Earth's mass was converted into chondrules (*13*, *14*). This assumed need to produce a planetary-scale mass of chondrules is a problem for most theories of their formation. However, later production of chondrules might allow conversion of much less mass. For example, in Wetherill's (*34*) model for the formation of the asteroid belt, most material in that region accreted into lunar-sized bodies before Jupiter formed, and these were removed by gravitational scattering and jovian resonances on a time scale of 10^8 years. Lunar-sized bodies would be too large for gas drag to bring them into resonances or to be ground into dust by collisions. Most of the mass in the asteroidal zone would be decoupled from the chondrule-forming process, except for the small end of the size distribution. Such a model demonstrates that chondrules as second-generation objects need not have been produced in the massive quantities generally assumed.

Our model provides a natural explanation for the age difference between CAIs and chondrules. Because high planetesimal eccentricities and strong bow shocks appear to require a fully formed, massive Jupiter, this interval would reflect the time between condensation of refractory matter in the nebula and the completion of Jupiter's growth. The inferred range in chondrule ages could also be a measure of how long the nebular gas persisted after Jupiter formed.

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35. We thank T. Swindle, T. V. Ruzmaikina, and J. A. Wood for discussions. Supported by NASA (S.J.W. and L.L.H.) and the Italian Space Agency (F.M.). This is Planetary Science Institute Contribution 343.

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Possible Production of High-Energy Gamma Rays from Proton Acceleration in the Extragalactic Radio Source Markarian 501

K. Mannheim

The active galaxy Markarian 501 was discovered with air-Cerenkov telescopes at photon energies of 10 tera–electron volts. Such high energies may indicate that the gamma rays from Markarian 501 are due to the acceleration of protons rather than electrons. Furthermore, the observed absence of gamma ray attenuation due to electron-positron pair production in collisions with cosmic infrared photons implies a limit of 2 to 4 nanowatts per square meter per steradian for the energy flux of an extragalactic infrared radiation background at a wavelength of 25 micrometers. This limit provides important clues about the epoch of galaxy formation.

Gamma rays (γ rays) from cosmic sources impinging on Earth's atmosphere initiate electromagnetic showers in which the energy of the primary γ ray is imparted among secondary electron-positron pairs. The blue Cerenkov light emitted by the pairs in the atmosphere can be detected from the ground with optical telescopes triggering on the short (~1 ns) optical pulses. The technique has advanced considerably in recent years (*1*), and some surprising discoveries have been made. Among them is the detection of the blazar Markarian 501 (Mrk 501) at energies above 10 TeV (1 TeV = 10^{12} eV) (*2*).

Blazars are remote but very powerful sources characterized by their variable polarized synchrotron emission. They are associated with radio jets (bipolar outflows) emerging from giant elliptical galaxies seen at small angles with the line of sight. Mrk 501 is $\sim 3 \times 10^8$ light-years from Earth but nevertheless produces a tera–electron volt γ ray flux during outbursts that is many times stronger than that of the Crab Nebula, a supernova remnant inside our Milky Way at a distance of only 6×10^3 light-years. The radiation mechanism responsible for the γ rays could be either inverse Compton scattering of low-energy photons by accelerated electrons (*3*) or pion production by accelerated protons. In the latter case, the sources could be among the long-sought sources of cosmic rays; that is, the isotropic flux of relativistic particles with differential number density (N) spectrum $dN/dE \propto E^{-2.7}$ (for energies $E < 10^3$ TeV), mainly consisting of protons and ions (*4*).

Particle acceleration in astrophysics is typically observed to be associated with (collisionless) shock waves when a supersonic flow of magnetized material hits a surrounding medium. Examples of shock waves are shell-type supernova remnants (explosion of a massive star), plerions (pulsar wind), γ ray bursts (relativistic ejecta from the collapse of a compact stellar object), or the jets ejected from active galactic nuclei (collimated relativistic wind from the accretion disk around a supermassive black hole).

In the theoretical picture of shock acceleration, relativistic particles (protons, ions, and electrons) scatter elastically off turbulent fluctuations in the magnetic field on both sides of the shock and thereby gain energy because of the convergence of the scattering centers (approaching walls). The acceleration time scale for the process can be written as $t_{acc} = \xi r_g c/\upsilon^2$, where υ denotes the velocity of the shock wave (c is the speed of light) and $r_g \propto E/B$ denotes the radius of gyration of a particle with energy E in a magnetic field of strength B. The effects of shock obliquity, turbulence spectrum, and other unknowns are conveniently hidden in an empirical factor $\xi \geq 1$. The most rapid (gyro–time scale) particle acceleration for relativistic shocks corresponds to $\xi = 1$ (*5*). Balancing the acceleration time scale with the energy loss time scale due to synchrotron radiation $t_{syn} \propto B^{-2} E^{-1}$, one obtains the maximum energy of the electrons $E_{max} = 10\ (\xi/10)^{-0.5}(B/3\mu G)^{-0.5}(\upsilon/10^8\ cm\ s^{-1})$ TeV (*6*). The observed 10-TeV γ rays from the Crab Nebula (*7*) and the observed synchrotron x-rays in shell-type supernova remnants (*8*) (corresponding to 10-TeV electrons) require $\xi \sim 1$ to 10. Because protons lose less energy, they can reach larger E_{max}'s than electrons and give rise to γ ray emission even above ~10 TeV by means of pion production and subsequent pion decay. Although shock acceleration theory predicts that most of the cosmic rays are accelerated in supernova remnants (*4*), no definitive γ ray signature has yet been discovered.

It has been argued that the assumption of electron acceleration also suffices to explain the γ rays from blazar jets such as Mrk 501 (*9*). Estimates of the magnetic field strength in the γ ray–emitting part of the jet in Mrk 501 then yield values in the range $B \sim 0.04$ to 0.7 G. This magnetic field is much stronger than the one in supernova remnants, and the associated stronger cooling of the relativistic electrons due to synchrotron energy losses reduces E_{max} accordingly. The effect is almost compensated for by the high shock wave velocities in extragalactic radio sources, which speed up the acceleration rate. Using radio interferometry, shock wave velocities close to the speed of light have been inferred, corresponding to typical bulk Lorentz factors in the range $\Gamma_{jet} = (1 - \beta^2)^{-0.5} \sim 2$ to 10 ($\beta = \upsilon/c$), with a few cases of still higher values (*10*). Because of the alignment of the jet axis and the line of sight in Mrk 501, superluminal motion has not been observed.

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