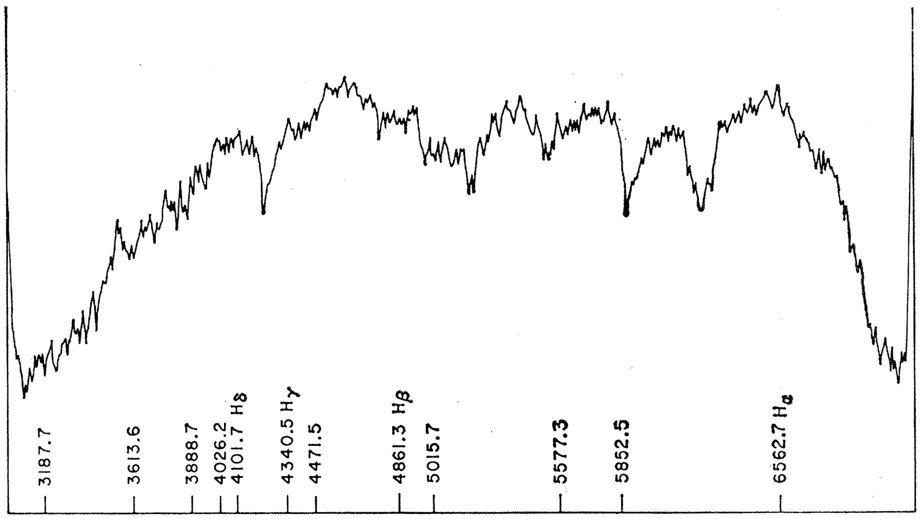

Fig. 2. Direct microphotometer tracing of the spectrum of the red pygmy star LP 101–15, as obtained with the prime focus spectrograph of the 200-inch (508 cm) telescope on emulsion 103a-F at a dispersion of 400 Å mm⁻¹.

bands, many sharp emission lines and a few distinct broad absorption lines. In view of the low sensitivity of the 103a–F emulsions in the green, some of the bright lines and bands in this part of the spectrum are of remarkable intensity.

Very distinct and deep absorption lines appear at 5890.2 Å and 4227.5 Å which must be identified with the lines λ5889.95 and 5895.92 of sodium and 4226.7 of calcium.

The Balmer lines H_α, H_β, H_γ, H_δ, and H_ϵ and the H and K lines of calcium appear in sharp emission. Unidentified remain the sharp emission lines at wavelengths equal to 6832.8, 6763.3, 6740.0, 6700.8, 6670.9, 5583, 3788, as well as broader and blended emission features at 3884.1, 6162.8 to 6287.8, and 3544.7.

None of the emission bands has been identified with certainty except the one at wavelength 4959.5 which is probably coincident with the band head of TiO at 4955. There remain, however, the features at 5175, 5208, 5445, 5487, and 5583 which might be the ZrO bands at 5185, 5439, 5456, and 5552. In this connection the sharp lines at 6832.8 and 6763.3 could be interpreted as being the ground level lines 6832 and 6762 of ZrI. If the presence of ZrO and Zr could be confirmed, this would suggest that LP 101–15 is the first dwarf representative of the interesting class of S-type stars in the spectra of whose giant members Merrill (*5*) first found the ZrO bands. No other dwarfs showing zirconium bands have been found.

A comparison of the spectrum of LP 101–15 with those of ordinary M dwarfs gave negative results. In particular its spectrum appears quite different from Wolf 47 (right ascension 0^h 57^m, declination +61°51′ Epoch 1900) which is an M5 dwarf of large proper motion (0.8 sec yr^{-1} in position angle 80°) and absolute visual magnitude $M_v \cong 12.6$. The apparent photographic magnitude of LP 101–16 is about + 15.3.

On the preliminary distance of 6 parsecs adopted in the preceding, its absolute magnitude therefore is of the order of + 16.3, making it visually about + 15.0 or 2.5 magnitudes below the main sequence.

From the discoveries of pygmy stars made during the past year it is to be expected that some still fainter (absolute) ones will be found to be nearer than any of the nearest stars. If the masses of these new stars are not all greatly inferior to that of the sun, they thus may contribute materially to the mass of the galaxy.

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3 May 1966

Chondrules: Suggestion Concerning the Origin

Abstract. *The millimeter-sized, sometimes glassy spheroids called chondrules that occur abundantly in stony meteorites may have been produced by lightning in the primitive Laplacian-type nebula while earthy materials were condensing and collecting to form the asteroids and the terrestrial planets.*

Stony meteorites contain small silicate inclusions, called chondrules, of the order of a millimeter in dimension (Fig. 1). The shape of the chondrules varies from almost perfectly spherical droplets to highly distorted figures. The occurrence of glasses indicates a quick cooling from the molten state. In some meteorites chondrules constitute a major fraction of the bulk. Sorby (*1*) thought that they came from Sun in the form of a "fiery rain." Suess (*2*) has suggested that they represent the most primitive material in meteorites, condensed in protoplanets. Wood (*3, 4*), and Levin and Slonimskii (*5*) proposed that chondrules condensed directly from the gaseous solar nebula that is believed to have predated the planets. In the Levin and Slonimskii process, solid chondrules were formed directly, a process that is difficult to support mineralogically, while in Wood's process liquid droplets were condensed and quickly chilled. The massive occurrence of chondrules in most of all known meteorites, in spite of the great losses that such small particles must have sustained owing to subsequent heating and metamorphosis, proves that chondrule formation must have been a nearly universal process, basic to the development of stony meteorites and, presumably, the asteroids. That the bulk composition of the chondrules is very similar to that of the matrix supports this concept. Thus, chondrule formation must have been essentially omnipresent near the asteroid belt or near the asteroids at some early period in the formation of the solar system.

Specialized mechanisms for chondrule formation, such as volcanic action or even hypervelocity-impact spraying, appear inadequate on the grounds that an insufficient fraction of the basic material could be so treated. Direct condensation as droplets from a cooling solar gas requires vapor pressures of about 10^2 to 10^3 atmospheres (*4*), too high to be likely in a Laplace nebula. Wood's suggestion that shock waves in a Laplace nebula might produce adequate melting and quick cooling of earthy "snowflakes" has yet to be demonstrated either theoretically or experimentally. Cameron's (*6*) suggestion that the final dissipation of magnetic fields in the original collapsing nebula might dissipate the plasma energy into heated droplets meets with serious difficulties. Particularly, we would expect the dust condensed in a cooling or collapsing nebula to destroy extensive magnetohydrodynamic fields gradually by recombining the free ions and electrons. The energy so released will be radiated away.

Let us now visualize the situation near the plane of an assumed Laplace-type nebula before a solar-type atmosphere has been fractionated. The atmosphere will be chemically reducing, mainly hydrogen. Increasing density and pressure in the contracting cloud will condense earthy material as dendritic dust flakes or dust aggregates. I prefer here to avoid the postulate of cooling from high temperatures. The high opacity of the dust cloud will exclude high-frequency radiation of all sorts. A low general background of cosmic rays will, of course, remain. Ionization and plasma characteristics will have disappeared to leave a gas-dust cloud of very low electrical conductivity. Large-scale turbulence will be present although the detailed character of such turbulence still remains in question. Gas clouds falling into the rotating nebula can also set up irregular turbulence. The dust will tend to aggregate and settle toward the plane of the ecliptic except as stirred by turbulence and by infall to growing asteroids.

The circumstances described are ideal for the production of lightning. We observe that wherever we have a dust-laden circulating or turbulent gas (or even liquid) that is a poor conductor, extremely high electrical potentials develop. These potential differentials break down as lightning. Water or concurrent condensation processes, as in thunderstorms, are not essential. Lightning occurs in "dust devils" of dry arid regions, in flour mills, and in stone-grinding mills.

We would expect the plasma "pinch" effect (*7*) in a lightning discharge to draw in the dust balls and to provide a compressive force on those existing in the early discharge region, producing molten droplets. The pinch effect is sometimes defined as the self-constriction of a cylinder of plasma current due to the pressure of its own magnetic field. The following crude theory will show that such a process is required if lightning has indeed produced the chondrules. Otherwise, prohibitively large sources of energy would have been required.

Suppose that, instead of the pinch effect, we should rely on high-energy radiation and shock phenomena near the flash to heat the dust flakes and to produce droplets in a cylindrical volume surrounding the flash. Let a dust ball of radius r and density ρ_d be located near a lightning flash of energy E_L (erg cm^{-1}). Suppose further that the dust ball absorbs energy proportionally to its area (πr^2) with 100 percent efficiency, and that this total energy at distance R from the flash is just equal to the energy to fuse the dust ball (ζ erg g^{-1}), from the ambient temperature in the gas-dust cloud. We find then that

$$R = 3E_L/8\pi\zeta\rho_d r \text{ cm} \quad (1)$$

If the entire volume of the gas-dust cloud is to be "treated" statistically by lightning, only $(1 - 1/e)$ of the dust will remain untreated. The corresponding total energy required per unit volume, E_v, to melt a dust ball to a distance R from each flash is

$$E_v = \frac{64\pi}{9}\frac{\zeta^2}{E_L}\rho^2_d r^2 \text{ erg cm}^{-3} \quad (2)$$

To insert numerical values, let us postulate dust balls of density, ρ_d, equal to 0.1 g cm^{-3} and radius, r, equal to 0.15 cm to give millimeter-diameter chondrules of normal density. The energy required to melt silicates from room temperature is ζ, about 2×10^{10}erg g^{-1}. Typical atmospheric lightning bolts discharge some 15 coulombs at 100 ev cm^{-1} (*8*), leading to E_L about equal to 1.5×10^9erg cm^{-1}. Hence, we find from Eq. 2 that E_v is about 1.3×10^9 erg cm^{-3}.

To estimate the total energy required per unit mass of nebular material, we must postulate the nature of the Laplace nebula. As a working model suppose that 100 Earth masses of earthy material were spread uniformly within Jupiter's present orbit and that 500 times this amount (3×10^{32}g) of lighter material, mostly hydrogen, constituted the inner part of the total nebula disk. The surface density would be 1.7×10^4g cm^{-2}. At 300°K, the gas pressure near the plane would be

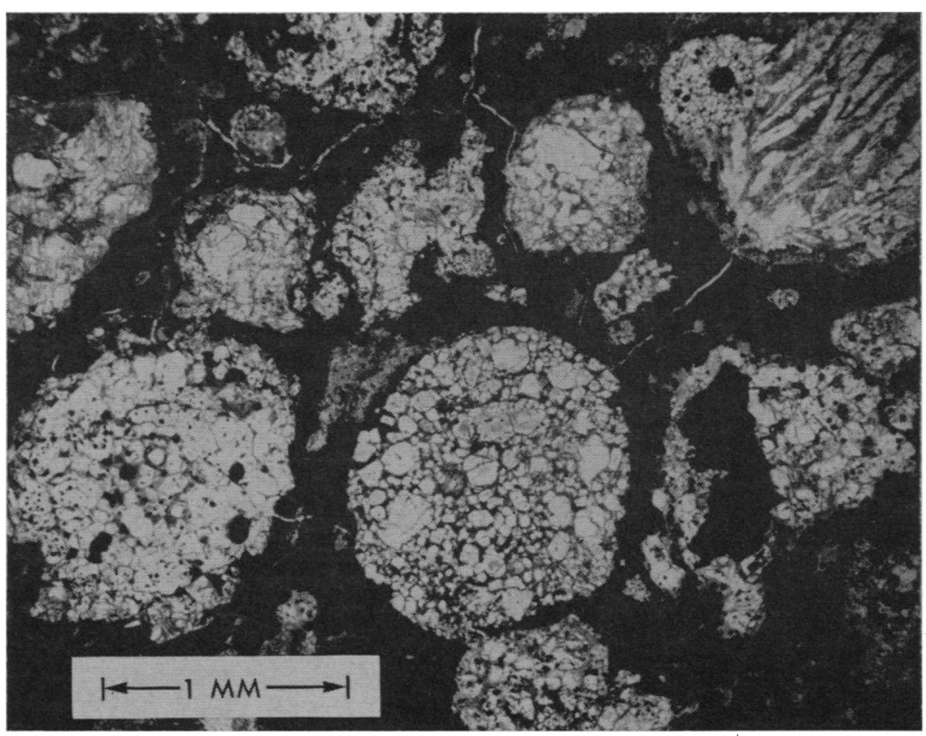

Fig. 1. Thin section of the carbonaceous chondrite *Renazzo*, viewed by transmitted light. The structure consists of rounded chondrules, embedded in an opaque, black matrix. Each chondrule contains numerous transparent (hence light) crystals of silicate minerals, chiefly olivine and pyroxene. The grayish material between silicate crystals inside the chondrules is, in many cases, glass. The matrix consists of ultra-fine-grained minerals of ill-defined composition and carbonaceous compounds (*15*).

4×10^{-5} atm and the gas density 4×10^{-9} g cm^{-3} (*9*). Thus, the required total release of energy by lightning to "treat" the gas would be $(1.3 \times 10^9)/(4 \times 10^{-9}) \geqq 10^{18}$ erg g^{-1}. This corresponds to the kinetic energy at a velocity of more than 10,000 km sec^{-1}, much too high to be supplied by turbulence fed by gravity. At most, we can expect parabolic orbital velocities of the order of 20 km sec^{-1}.

We see from Eq. 2 that the equivalent kinetic velocity to feed the lightning process within the total volume varies as $(E_L)^{-1/2}$. Hence, if lightning flashes of 10^5 to 10^6 times greater energy per unit length than those typical of our atmosphere can occur in the primitive nebula, the energy requirement can be reduced to a reasonable velocity, equivalent to some tens of km sec^{-1}. The maximum-energy lightning flashes observed in the atmosphere are 10 times more energetic than our adopted average. At lower densities, however, the breakdown voltage decreases (*10*), and thus possibly reduces the linear energy of lightning in the primitive nebula. We can reduce the energy discrepancy only slightly by postulating that the energy of the lightning is not entirely lost to the system by kinetic motion of the gas and subsequent radiation to space. Only a moderate fraction could appear again as lightning. Nor will raising the temperature of the gas near to the limit for glass formation provide much assistance. Radiation from the young Sun seems to serve no useful end in the process.

On the other hand, the energy adopted above for a lightning flash may be much overestimated, and we should look at the phenomenon differently. Uman and Orville (*11*) find that the maximum temperature indicated by the N II lines in lightning is some 25,000°K. For N atoms this corresponds to a kinetic equivalent velocity of only 7 km sec^{-1}. Adding dissociation (9.8 ev), ionization (14.5 ev), and excitation for N_2, we find a total equivalent kinetic velocity of just under 20 km sec^{-1}. Thus, all the matter in a Laplace nebula could, by these crude energetic considerations alone, be subjected to lightning. If, then, the pinch effect acts on all of the dust balls in the original gas column collapsed by a lightning flash, we may reasonably postulate enough energy to produce chondrules by this process.

The lightning might be somewhat confined to the turbulent temporary atmospheres of developing asteroids. Here the heated droplets could fall immediately into place, and the requirement that all of the material be heated by lightning would be reduced.

Note that lightning could provide free energy for forming complex carbon compounds in asteroidal bodies, as in Miller's (*12*) experiment. Thus, the occurrence of such material (*13*) in carbonaceous chondrites might be anticipated.

The little-understood process of particle aggregation in the Laplace nebula could be greatly accelerated by the occurrence of charges on the small condensed flakes or on chondrules. It is possible that the restricted limits to chondritic dimensions were controlled by electrostatic-charge limitations on the original dust balls as well as by limitations in the lightning processes.

Clearly much research, theoretical, observational, and experimental, is needed to evaluate this suggestion that lightning produced the chondrules. I note that, for at least two decades, Bruce has advocated that lightning plays an important role in cosmic phenomena. In none of his papers, however, have I been able to find a suggestion regarding its possible occurrence in the primitive solar-system nebula or as a factor in the production of chondrules (*14*).

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Martian Wave of Darkening: A Frost Phenomenon?

Abstract. *A new hypothesis attributes the Martian "wave of darkening" to soil frost phenomena. Diurnal thawing and freezing of the ground, which uses moisture transported by the atmosphere from the melting polar cap, can produce various minute, frost-heaved, soil surface features. These microrelief features result in a complex porous surface structure, which causes optical darkening. The boundary at which the wave of darkening terminates on the winter hemisphere correlates with the latitude at which the diurnal peak surface temperature drops below 0°C. The hypothesis is examined in terms of known properties of the Martian atmosphere and surface and the availability of water.*

The Martian "wave of darkening" is ascribed to frost phenomena in a new hypothesis not based on vegetation. It is suggested that freezing during the Martian afternoon and evening produces one or more types of surface microrelief features similar to those observed in areas where frost action occurs on Earth. These frost features can diminish reflectivity by increasing the complexity of the surface.

Miniature soil columns and similar features, referred to here as "microhills," raised by formation of needle ice, have been observed in Pennsylvania to form in certain areas of wet soils after freezing nights. Typically, the microhills are very rough columns, from a few millimeters to several centimeters high, with a height-diameter ratio of 2 to 5, spaced singly or in clusters or subparallel ridges over many square meters. The observed microhills fall into the category of frost phenomena associated with needle ice described by Troll (*1*), who states: "Needle ice formed in fine-grained bare or sparsely vegetated soils (clay, loess, marl, shale and peat) with no snow cover or at most a slight covering of snow, by the abrupt freezing on the surface of the ground, most frequently by night freezing due to radiation loss."