1-15-1976

Grains of Anomalous Isotopic Composition from Novae

Donald D. Clayton
Clemson University, claydonald@gmail.com

Fred Hoyle
Rice University

Recommended Citation

Please use publisher's recommended citation.

1976ApJ...203..490C

THE ASTROPHYSICAL JOURNAL, 203:490–496, 1976 January 15

GRAINS OF ANOMALOUS ISOTOPIC COMPOSITION FROM NOVAE

DONALD D. CLAYTON AND FRED HOYLE*
Department of Space Physics and Astronomy, Rice University

Received 1975 April 28; revised 1975 June 26

ABSTRACT

We study the effects of grain formation in nova ejecta with double purpose: (1) to schematically model the optical and infrared luminosities, (2) to identify the anomalies of isotopic composition that should be present in large abundance in these grains. The large carbon concentration makes the rapid and efficient grain formation possible, and accounts for the peculiar luminosities observed in Nova Serpentis 1970. In the anticipated range of nova conditions, rapid addition of hot protons during the outburst produces large overabundances of ^{13}C, ^{18}O, ^{22}Na, ^{26}Al, ^{30}Si, and perhaps others. Anomalous ^{14}C is expected subsequent to the ^{13}C(α, n)^{16}O reaction, and will be trapped in grains formed by subsequent atmospheric loss. Each of these anomalies may have been detected, either on the Moon due to accretion of interstellar dust or in the carbonaceous chondrites. Perhaps nova grains are responsible.

Subject headings: planets: abundances — infrared: sources — Moon — stars: novae

I. GRAIN FORMATION IN NOVAE

We begin by considering the formation of graphite grains in nova shells. The first point is that carbon is expected to be a major constituent of the nova envelope. The nova models calculated by Starrfield *et al.* (1975) require ejected material to be rich in carbon, by as much as a factor of 10 to 100 for those models based on a discussion by Hoyle and Clayton (1974, designated HC). The formation of graphite grains has been analyzed quantitatively by others (e.g., Donn *et al.* 1968), and we find the nova environment to be appropriate.

It will be our point of view unless stated otherwise that radiation from an underlying star provides the energy source for emission by the expanding nova shell. We take the output L from the star to decline from $\sim 10^5 L_\odot$ during the first 10 to 20 days to $\sim 2 \times 10^4 L_\odot$ after 50 days. This underlying luminosity is shown as a dashed line in Figure 1, which we offer as a schematic model of this general class of events. The value $2 \times 10^4 L_\odot$ was selected to be about half of the maximum infrared emission observed for Nova Serpentis 1970 by Geisel *et al.* (1970, designated GKL). Their observations show that grain formation must be very extensive in the ejecta. They argued that at least $10^{-6} M_\odot$ of grains are needed after 90 days for the

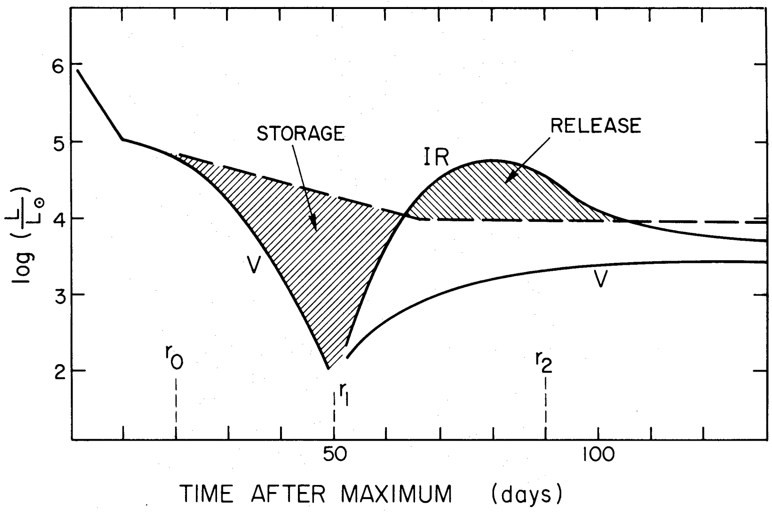

FIG. 1.—The visual and infrared luminosities of the model as a function of time. The total luminosity of the underlying star is shown as a dashed line joining the visual luminosity at early times. The special shell radii r_0, r_1, and r_2 relevant to the opaque model are explained in the text, as are the storage and release mechanisms.

---

* Visiting Professor, 1975 April.

infrared maximum of $5 \times 10^4 L_\odot$. We will first present a model having an infrared luminosity well in excess of the luminosity of the underlying star, as called for by GKL. This model will store radiation throughout a large cavity due to a high opacity of a shell of grains and will release it as that opacity falls.

To store sufficient infrared energy, the model requires the grains to form in ejecta moving sufficiently fast to have sufficient volume at the time the radiation is to be released. To achieve this, we take the outer surface of the shell to expand at a speed indicated by the Doppler shift of the lines of the diffuse enhanced spectrum rather than by the smaller Doppler shifts of the first absorption lines to be seen. Typically, this gives an expansion speed of $\sim 2000 \text{ km s}^{-1}$ (Payne-Gaposchkin 1957, p. 294), which is adequate for our model. Against this view, McLaughlin (1960) argues that the diffuse enhanced spectrum originates inside the slower moving principal spectrum, which in this case has a maximum of 1000 km s^{-1} (Grygar and Hutchins 1970), but is more representatively about 700 km s^{-1} (J. C. Gallagher, private communication). Payne-Gaposhkin (1957, p. 80) observes on the other hand that, if the strong diffuse enhanced spectrum is interior to the principal spectrum, it should overtake it (in a week or two for Nova Serpentis 1970), whereas the slow moving principal spectrum is in fact almost constant, sometimes even decelerating. We will not enter this controversial area of interpretation, but instead are content to provide a new and interesting set of combined light curves if a substantial portion of the early ejecta does move with the diffuse enhanced speed. We would speculate that the associated spectrum might not be recognizable for the first week or so due to an initially high ionization state providing the early peak continuum (whereas the later continuum emerges from the effective photosphere of the underlying star). We will take the total mass of this emitted shell to be about $3 \times 10^{-4} M_\odot$.

Writing r for the distance of an imagined shell of material from the central star, carbon grains form as r increases to a value r_0 such that $[L/\pi\, acr_0^2]^{1/4}$ falls to the condensation temperature of graphite grains. For densities of the order of those in nova shells the condensation temperature is ~ 2000 K. Setting $L \approx 10^5 L_\odot$, this condition gives $r_0 \approx 1.8 \times 10^{14}$ cm, which would be reached by the expanding material in about 11 days at the speed 2000 km s^{-1}. The onset of grain formation would be expected to coincide with the beginning of infrared emission. GKL found that moderate infrared emission from Nova Serpentis 1970 already existed after 19 days, with a color temperature of about 1500 K rising thereafter to about 2000 K. Within the aforementioned uncertainties of the value to be attached to L and to the expansion velocity, these observations are in satisfactory agreement with our estimate of 11 days and with a grain temperature of ~ 2000 K.

Not all carbon will fall out of the expanding gas at this distance from the underlying star. This would be true even if nucleation and growth were instantaneous. If it were to do so, the opacity would become too large and the resulting holding back of the radiation from the central star would raise the effective temperature of the grains, causing them to evaporate. To see this and subsequent conclusions, consider for a moment that the shell is thick to radiative transfer and that the luminosity L of the central star is forced to diffuse through it. The gradient of the radiant energy density through the shell can be written

$$\frac{d}{dr}(aT^4) = -\frac{3\kappa\rho}{c}\frac{L}{4\pi r^2}\,. \tag{1}$$

Defining the radiative thickness $\tau = \int \kappa\rho dr$ of the shell, the inner and outer radiative energy densities differ by

$$U_{\gamma,\text{in}} - U_{\gamma,\text{out}} = \frac{3L}{4\pi r^2 c}\,\tau\,. \tag{2}$$

Thus the energy density of the radiation field in which the grains are embedded increases proportionally to the optical depth τ. If the grains could precipitate immediately at r_0, τ would become greater than unity and $U_{\gamma,\text{in}}$ would be so great as to evaporate the grains, reducing τ. With instantaneous grain growth, therefore, $\tau \approx 1$ at $r = r_0$. As r increases above r_0, τ can increase above unity, however, provided $\tau(r_0/r)^2$ remains constant (assuming L does not change). Indeed, so long as carbon continues to be able to condense, τ will increase at constant L as $(r/r_0)^2$, and can increase even faster if the radiant flow L decreases due to storage of energy. The optical luminosity of the nova then falls as $e^{-\tau}$. This model produces the rapid fall of visual luminosity up to 50 days in Figure 1.

Suppose grain condensation ceases at $r = r_1$, as it might if the condensibles became exhausted in the shell, or if nucleation and growth becomes too slow due to the low density of condensibles. Thereafter, the optical depth will decrease like $r_1^4/r_0^2r^2$, and the optical luminosity of the nova will increase. The attenuation of the optical light from the underlying star is therefore determined by

$$\begin{aligned} &\exp\left[-\left(\frac{r}{r_0}\right)^2\right], \quad r_0 < r < r_1\,, \\ &\exp\left(-\frac{r_1^4}{r_0^2 r^2}\right), \quad r_1 < r\,, \end{aligned} \tag{3}$$

the minimum optical luminosity occurring at $r = r_1$. These special shell radii are marked in Figure 1. Novae with deep minima show a decline of ~ 7 mag, implying $r_1 \approx 2.5\, r_0$. Thus if r_0 were attained after 19 days, as in the observations of GKL, r_1 would be reached after ~ 48 days. (These remarks take no account, of course, of energy that may reach the surface of the expanding material by mechanical means, say through shock waves that might continue to be propagated outward by the underlying star. Mechanical energy converted to heat, and thence to radiation at the surface, could add to both the optical and infrared luminosities.)

GKL also found a decline between 19 days and 50 days of the infrared luminosity. This we attribute to storage of radiation occasioned by increasing opacity. The inner surface reradiates into the enclosed volume, so that the luminosity traversing the shell is actually less than L. The relevant condition is that a sphere of radius r_1 be filled with radiation at an effective temperature of ~ 2000 K, and that the total enclosed energy account for the observed deficit. Using $L \approx 2 \times 10^4 L_\odot$ for the output of the underlying star during this radiative accumulation, the time t_1 required is given by

$$t_1 = \frac{4}{3}\pi r_1{}^3 a(2000)^4 \frac{1}{2 \times 10^4 L_\odot} . \tag{4}$$

The radius r_1 reached after 50 days, for an expansion speed of 2000 km s^{-1}, is 8.6×10^{14} cm. Inserting this value of r_1 in equation (4) gives an accumulation time t_1 of ~ 50 days. The two estimates of the time are consistent. A delay of this order, before the infrared luminosity rises to its maximum value, is therefore to be expected. After the cavity has been filled, the shell must transmit the entire luminosity L. As r increases above r_1, the infrared luminosity must of course increase because the opacity then decreases in the infrared as well as in the optical and the surface increases. As the opacity decreases, the reservoir of radiation accumulated for $r < r_1$ also escapes, augmenting the output of the underlying star—the earlier deficit of emission being then compensated by an excess. The reservoir of excess energy totals 3×10^{44} ergs, as required to fit the facts. During the same period, the grain temperature must decrease markedly on this model, just as observed by GKL.

GKL found a maximum infrared luminosity of $\sim 5 \times 10^4 L_\odot$ occurring after 90 days. At this stage $r \approx 1.8 r_1 \approx 1.5 \times 10^{15}$ cm $= r_2$, say. The opacity, given approximately by $r_1{}^4/r_0{}^2 r_2{}^2 \approx 2$, approached the condition where radiation could escape comparatively freely from the nova shell. For Nova Serpentis 1970, opacity in the infrared and in the optical seem to have been roughly comparable, implying a rather large grain size, say a grain diameter of about 5 μ. The total mass of condensed carbon seems therefore to have been of the order of a layer of thickness 5 μ covering a sphere of radius r_2, i.e., $\sim 3 \times 10^{28}$ g. Taking $\sim 3 \times 10^{-4} M_\odot$ for the total shell mass, the condensed carbon thus appears to have made up about 5 percent of the total mass, an estimate well within the range of models permitted by the work of HC. These gave carbon concentrations up to 90 percent in the extreme cases where the white-dwarf carbon nuclei outnumber the admixed protons. Indeed, much of the carbon could have remained in vapor form without there being a contradiction with the circumstellar dust models described here.

At this point we note that this rate of dust injection into the interstellar medium is not insignificant. If the rate of such events is 10 per year and if the average residence time of interstellar dust is 10^9 yr, then the steady concentration of nova dust exceeds $10^5 M_\odot$ which is about 10^{-3} of the total dust mass. Condensates other than carbon will exist due to other elements (O, Ne, Mg, Si, S, Ca, Ti, Fe) present in the accreted envelope of the white dwarf. Although we take the view that the abundant early condensate in Nova Serpentis 1970 is carbon, white dwarfs of heavier composition can also become novae and can eject large amounts ($\sim 10^{-4} M_\odot$) of condensable material, also of unusual isotopic composition. We return to these grain anomalies later.

Despite the many successes of this model, which we might call an "opaque model," there are other considerations which present difficulties. The first was mentioned at the beginning—that, if we are to store 3×10^{44} ergs in 50 days, the dust must condense from a shell moving at speeds well in excess of the mean Doppler shifts of the principal spectrum. Thus we would require that the principal spectrum be a "standing feature" associated with continuous outflow from the star well within the dust shell. Considering the lack of firm understanding of these spectra, this may well be possible.

Another important set of facts come from the ultraviolet measurements of Nova Serpentis 1970 as obtained from OAO–A2 (Gallagher and Code 1974). They show that the nova became progressively bluer during the fall of the light curve, and, with considerable uncertainty in the correct amount of ultraviolet extinction, the combined optical and ultraviolet luminosities remained constant (to within a factor 2) for about 53 days following visual maximum. They suggest that the underlying luminosity remains constant, but that the observed output suffers a redistribution from optical to ultraviolet as the overlying optical depth decreases. Since the ultraviolet rises as the optical falls, there can be no thickening dust on that picture—at least for the first 53 days. On this picture, which might be called an "optically thin" model, the rapid rise of the infrared luminosity between days 50 and 60 represents the onset of extensive grain formation. Since more than $10^{-6} M_\odot$ of dust is needed (GKL), some reddening and reduction in ultraviolet would be demanded at that time, but unfortunately the ultraviolet observations do not continue that long.

If, on the other hand, our opaque model of the light curves is to be correct, the ultraviolet luminosity must be external to the forming dust. In this case, the energy for the growing ultraviolet emission must be from a growing interaction of the fastest ejecta with surrounding nebulosity. A few times $10^{-6} M_\odot$ ejected at speeds of 2000 km s^{-1} and greater could, perhaps, shock heat a surrounding nebulosity in a way to produce a growing ultraviolet emission. If this picture is the correct one, the ultraviolet luminosity will have not decreased as the infrared rose before day 60. Unfortunately, the measurements do not exist.

Another advantage of the opaque model is that the visual luminosity recovers as the infrared maximum grows, just as is observed in nova light curves past the deep transition minimum. On the thin model, it is not clear why the visual luminosity should recover just as dust is forming. The opaque model could give a complicated early decline of the peak infrared luminosity, as observed, because the grains have a much lower luminosity after the trapped energy in the reservoir has leaked out. On the other hand, the thin-model infrared luminosity should seem to fall somewhat more slowly than t^{-2}, since some grain formation presumably continues past the infrared maximum, thereby rendering the distance dependence less than r^{-2}. The opaque model also is consistent with the rapid cooling of the dust near optical minimum (roughly 2000 K to 1000 K between days 40 and 60).

It is perhaps not possible to say with assurance which model of the postnova luminosity curves is the correct one. Perhaps other conversions of mechanical energy are occurring. In either case, however, of order 10^{28} g of dust has precipitated from nova ejecta. For the science of cosmochemistry, this can be taken as evidence of grains formed in explosions.

II. ISOTOPIC PECULIARITIES

We next turn our attention to the isotopic compositions of the elements in nova dust grains. The following subsections describe the most notable isotopic anomalies that would be expected. We will then point out that each of them may have already been detected.

a) ^{13}C

The first feature is that most of the stable carbon is ^{13}C, whether one considers the heavily enriched models of HC or the moderately enriched models of Starrfield *et al.* (1972). Objects containing variable mass fractions of nova grains will therefore have variable $^{13}C/^{12}C$ abundance ratios. Our estimate, that $\sim 10^{-3}$ of interstellar carbon resides in nova grains, suggests that $\sim 10^{-1}$ of interstellar ^{13}C resides in nova grains. The remainder of interstellar carbon is either gaseous or in grains formed in a different class of objects. Large ^{13}C anomalies can therefore be expected in bodies having larger-than-average admixtures with nova grains.

b) $^{14}C(\tau_{1/2} = 5730\ \mathrm{yr})$

An interesting prospect of the heavily enriched models is that $^{13}C(\alpha, n)^{16}O$ can continue in the postnova star (see HC and also Starrfield *et al.* 1975). Large ^{14}C concentrations result from $^{13}C(n, \gamma)^{14}C$ in the most ^{13}C-rich scenarios, and smaller but substantial ^{14}C concentrations result from $^{14}N(n, p)^{14}C$ in the less ^{13}C-rich scenarios. Combined overabundances of ^{13}C and ^{14}C can result; and if mass continues to be lost from these distended postnova envelopes, condensing grains may be rich in ^{14}C and the *s*- and *r*-process heavy elements. The most noticeable eventual result would be the correlation of a pure ^{14}N gas in refractory grains rich in ^{13}C. Since it is probably unreasonable to assume that more than 0.1 of all ^{13}C ejected in nova grains is from these heavily enriched cases, the ^{14}C concentration may be an order of magnitude less in bulk than the concentration of anomalous ^{13}C.

c) ^{18}O

The ^{16}O present when the temperature flashes to the point of rapid proton addition will be converted to heavier isotopes of oxygen by the sequence $^{16}O(p, \gamma)^{17}F(p, \gamma)^{18}Ne$, followed by subsequent positron emissions (before grain formation). The $^{17}F(p, \gamma)^{18}Ne$ reaction is probably as fast as that of the $^{16}O(p, \gamma)^{17}F$ reaction in the temperature range where the latter is rapid (above about $T_8 = 3$). The $^{17}F(\gamma, p)^{16}O$ reaction provides substantial resistance to this conversion above $T_8 > 3$, but not enough to quench the flow. Thus the sequence can go all the way to ^{18}Ne unless the proton deficiency limits the capture, as might occur in the most enriched HC scenarios. For the largest percentage of the novae, in which $H/(C + O) \geq 2$ initially, we expect the major oxygen anomaly to be enrichment of ^{18}O, and in some cases ^{17}O. For pure ^{12}C dwarfs, the ^{13}C anomaly would exceed the ^{18}O anomaly by variable amounts, depending upon the C/H enrichment scenario; but in dwarfs containing $O \gtrsim C$, the ^{18}O anomaly could much exceed the ^{13}C anomaly. As much as $\sim 10^{-1}$ of interstellar ^{18}O nuclei could reside in nova grains. The average relative yields of anomalous ^{13}C and ^{18}O depend on the spectrum of dwarf compositions and mixing scenarios, and cannot be given at this time.

d) $^{22}Na(\tau_{1/2} = 2.6\ \mathrm{yr})$

The ^{20}Ne present when the temperature flashes to the point of rapid proton addition will be converted ultimately to heavier isotopes of neon by the sequence $^{20}Ne(p, \gamma)^{21}Na(p, \gamma)^{22}Mg$, followed by subsequent positron emission. The gamma radiation following ^{22}Na decay has been suggested by Clayton and Hoyle (1974) as a test of nova theory and of supernova theory (Clayton 1975*a*), and the daughter ^{22}Ne has already been suggested by Clayton (1975*b*) as the source of meteoritic Ne-E (Black 1972). We reaffirm those ideas here, and point out that the relative average yields of ^{22}Na and ^{13}C depend upon the as yet unknown spectrum of white-dwarf compositions and mixing scenarios. In particular, a limit to the ^{22}Na concentration is not easily set because it is not known if a white dwarf can be rich in ^{20}Ne or whether one should utilize only the ^{20}Ne accreted from the primary star. Overabundant ^{21}Ne can also result if proton addition is limited by proton supply or by temperature, but it would be understandably more difficult to condense the noble gas ^{21}Ne than reactive ^{22}Na. In nova grains we therefore expect the ^{22}Ne anomaly to greatly exceed the ^{21}Ne anomaly (in absolute amount). It does seem possible, however, that neon trapped directly from the gas phase, as opposed to ^{22}Na, could be mistaken for spallation neon.

e) ^{26}Al($\tau_{1/2} = 7.4 \times 10^5$ yr)

The ^{24}Mg present initially will be rapidly converted to heavier isotopes provided the fuel enrichment due to mixing was sufficient to generate a peak temperature exceeding that required for rapid proton addition ($T_8 \approx 5$). The sequence is similar to those preceding: ^{24}Mg $(p, \gamma)^{25}$Al$(p, \gamma)^{26}$Si, followed by positron emissions to ^{25}Mg and to ^{26}Al. The relative yields depend strongly on the details of the scenario, and the limit to the absolute yield depends upon whether ^{24}Mg-rich white dwarfs exist. Since such white dwarfs are probably in the minority and since $(^{26}\mathrm{Mg}/^{24}\mathrm{Mg})_\odot$ is not really a small number, we may conclude that the fraction of interstellar ^{25}Mg and ^{26}Mg residing in nova grains is probably less than the cases of ^{13}C and ^{18}O—say 10^{-2} to 10^{-3}. Thus the magnesium anomalies would be smaller, but perhaps still detectable. Chemical fractionation of Mg/Al could clearly correlate with ^{25}Mg/^{26}Mg anomalies.

f) ^{30}Si

For peak temperatures approaching 10^9 K, the seed ^{28}Si is converted to ^{30}S by two rapid proton captures. The resulting nova grains will be highly ^{30}Si-rich; but, as in the magnesium case, it is unlikely that more than 10^{-2} to 10^{-3} of all interstellar ^{30}Si can reside in this concentrated form.

Other less abundant anomalies could, in the same spirit, be suggested, but we will not try to carry the identifications further here. Nor do we wish to discuss the fact that many of the same anomalies could be expected in grains forming in those red-giant atmospheres that have mixed CNO products and *s*-process products to their surfaces. Rather does it seem more stimulating to call attention to these most likely anomalies and to suggest that each may have been observed already.

III. OBSERVED ISOTOPIC ANOMALIES

To observe anomalies in solar-system objects due to these grains, it is of course necessary that complete vaporization in an isolated solar nebula has not occurred. Fortunately, that is the case. The discovery of anomalous ^{16}O by Clayton *et al.* (1973) has shown that at least 10^{-2} of carbonaceous-chondrite oxygen and at least 2×10^{-3} of terrestrial and lunar oxygen has arrived in grains that never vaporized. Clayton (1975*c*) has defined $f_A(\underset{\sim}{x}, t)$ as the fraction of species A in the early solar nebula that was trapped in grains that already existed prior to the solar nebula, and he has argued that it should be as high as 0.1 for refractory elements at the time solid bodies were forming. It is apparent in that picture that sizable grain-produced anomalies are possible. It is not clear what fraction of these grains were precipitated in novae, but our earlier reasoning suggested that 10^{-3} of the interstellar grains may be of this type. Within this framework we may therefore think of 10^{-4} as a reasonable estimate of the fraction of solar grains that had their origins in novae. To the extent that these grains were incorporated uniformly into objects, uniform bulk isotopic compositions will result. However, different objects having, for whatever reason, differing admixtures of nova grains will also have differing isotopic compositions correlated graphically with each other by mixing lines.

One evidence of admixture of nova grains may be the Ne-E discussed by Black (1972) and Eberhardt (1974), for it may be ^{22}Ne from ^{22}Na decay which exists today at the observed level of 10^{-12} g per gram of carbonaceous chondrite. This low level could be easily accounted for, even after extensive dilution with solar made grains. Clayton (1975*b*) has presented the case for interpreting meteoritic Ne-E in terms of such grains. If the lunar surface has accreted interstellar grains, as Clayton (1975*c*) argued from unsupported fission xenon, even larger concentrations could be present there, because one might find relatively undiluted samples of interstellar grains. Although a ^{22}Ne anomaly might be expected to be hard to detect by stepwise heating due to admixtures with solar-wind neon and spallogenic neon, it is noteworthy that Frick *et al.* (1975) have found a lunar feldspar correlation line corresponding to an intercept ^{22}Ne/^{21}Ne $\approx$ 80, a very high ratio for the trapped component.

It is of interest that other anomalies have been detected in the lunar soils that could be related to infalling nova grains which have been compacted as surficial contaminations of lunar breccia. Epstein and Taylor (1975) have found in lunar soils rather large positive anomalies in ^{13}C, ^{18}O, and ^{30}Si that are surface correlated. The fractional enrichments of these isotopes in the surface component are at least as large as δ^{13}C, δ^{18}O, δ^{30}Si equal to +200, +55, +30 (each $\times 10^{-3}$), respectively. The value of δ^{13}C may in fact be much larger, and for purposes of this argument we find it suitable to utilize the highest concentrations of anomalous ^{13}C. These were found in sample 70011, where removal of a skin comprising 0.8 percent of the sample lowered δ^{13}C from +14.8 to −5.8. The value of δ^{13}C in the skin must be large, ranging from $\delta^{13}\mathrm{C} = 2600$ if the carbon concentration were uniform down to $\delta^{13}\mathrm{C} \approx 200$ if the surface carbon concentration is a factor of 10 greater than that of the bulk sample. In either case, the removed skin contained about 3×10^{-6} g per gram of anomalous ^{13}C. Letting ^{13}C*, ^{18}O*, and ^{30}Si* designate the excess total concentration of these nuclei in the skin, we estimate $^{13}\mathrm{C}^* \approx 3 \times 10^{-6}$ g per gram, $^{18}\mathrm{O}^* \approx 4 \times 10^{-5}$ g per gram, and $^{30}\mathrm{Si}^* \approx 2 \times 10^{-4}$ g per gram.

From the point of view of nova grains it is puzzling that the ^{30}Si* concentration is the greatest and the ^{13}C* concentration the least, whereas we would have expected novae to eject them with the ^{13}C* being greater. On the other hand, the ^{30}Si* grains may have a greater probability of surviving intact. Most of the interstellar silicates were not formed in novae, moreover, so the large ^{30}Si* may instead reflect more abundant silicate grains formed in the ejecta of explosive oxygen or carbon burning, where δ^{30}Si can also be positive.

We should point out that good evidence also exists for interpreting these isotopic anomalies in lunar soil in terms of isotopic fractionation associated with large-scale losses of the lighter isotopes from the Moon (Clayton *et al.* 1974). Sputtering due to solar-wind and micrometeorite impact is required to have removed several percent of the mass of the lunar regolith from the Moon.

Becker and Clayton (1975) present fairly large variations of δ^{15}N, which are interpreted by them as variations in ^{15}N. However, our view of their stepwise-heating data suggests instead a source of pure ^{14}N released from a specific mineral at a temperature about 1000° C, above which δ^{15}N returns to its previous value. A value $\delta^{14}\mathrm{N} \approx +50$ would be required in the 1000° C fraction, and we wish to suggest it as a ^{14}C derivative from carbon-bearing nova grains. From grain-size separates, one finds that total nitrogen is in fact surface correlated and, on our picture, richest in ^{14}N (Muller 1974; Goel *et al.* 1974). By taking the 1000° C fraction to be 24 parts per million we estimate the concentration of anomalous $^{14}\mathrm{N}^*$ to be $\sim 10^{-6}$ g per gram, a value not out of line with the other anomalies discussed above. The rough correlation between high ^{40}Ar/N and high δ^{14}N (Yaniv and Heymann 1972) also fits this picture, because apparently "unsupported ^{40}Ar" would have its highest concentration in presolar-grain–rich mixtures (Clayton 1975*b*). Furthermore, we would interpret the anticorrelation of δ^{15}N with δ^{21}Ne (Kerridge 1975) as a positive mixing correlation between $^{14}\mathrm{N}^*$ and $^{21}\mathrm{Ne}^*$, where the latter might have been accreted from ^{21}Ne-rich nova gases rather than by spallation. The correlation apparently requires that, in the ensemble of nova grains, $^{14}\mathrm{N}^* \approx 5\,^{21}\mathrm{Ne}^*$. Notice however that the nitrogen *gas* ejected by the nova, as opposed to the ^{14}C-derived ^{14}N, is actually ^{15}N-rich, so positive $^{15}\mathrm{N}^*$ is also a possible result of nova grains. A correlation with entrained gases would therefore be complicated. A correlation of δ^{15}N with δ^{21}Ne in temperature fractions might reveal surprises despite the anticorrelation in lunar soil. To test our idea of a ^{14}C source it will be important to look for an $^{14}\mathrm{N}^*$ release near 1000° C in carbonaceous chondrites—a feature predicted by the nova-grain origin of $^{14}\mathrm{N}^*$.

Finally we wish to turn to anomalous ^{26}Mg. Gray and Compston (1974) and Lee and Papanastassiou (1974) have both detected Mg anomalies in the Allende meteorite. Gray and Compston (1974) present a good case for there being a ^{25}Mg anomaly that correlates with Al/Mg and that it is probably due to ^{26}Al decay. On the normal view of a once totally gaseous solar system, it is hard to understand how detectable levels of relatively short-lived ^{26}Al could survive. Therefore, Gray and Compston (1974) speculate about high-energy protons in the early solar nebula. On the other hand, Clayton (1975*b*, *c*) has emphasized that short-lived species may easily be trapped in grains formed in the explosive events themselves, and he argued that ^{22}Na, ^{26}Al, ^{129}I, and part of ^{244}Pu owe their daughter anomalies to such events. The detection of ^{26}Mg anomalies certainly supports that view. The excess $^{26}\mathrm{Mg}^*$ is about 0.4 percent of ^{26}Mg, in aluminum-rich chondrules where $\mathrm{Al/Mg} \approx 10$, a very high value. As we argued earlier, suppose 10^{-3} of interstellar ^{26}Mg is in nova grains, in which it was originally ^{26}Al. Now enrich Al/Mg by a factor 10^{+2} as is the case for this aluminum-rich inclusion, in which case 0.1 of its ^{26}Mg is from the ^{26}Al parent. Now dilute with solar grains, taking $f_{\mathrm{Mg}} \approx 0.1$, as argued by Clayton (1975*c*). It follows that 10^{-2} of that sample of Mg is due to ^{26}Al decay, which can result in the observed $\delta^{26}\mathrm{Mg} \leq 10^{-2}$. Lee and Papanastassiou (1974) found a much more complex system of Mg anomalies, including some negative values for δ^{26} (or, equivalently, positive values for δ^{25}). They therefore express skepticism regarding a simple ^{26}Al interpretation. We must point out, however, that the nova grains will be rich (relative to ^{24}Mg) in both ^{25}Mg and ^{26}Al. This is because seed ^{24}Mg is not converted fully to ^{26}Al; some is arrested as ^{25}Mg, depending upon the details of the nova model. Fractionation of ^{25}Mg from ^{26}Al in the grain precipitation will, therefore, ultimately result in small samples having positive anomalies for *both* heavy isotopes; *i.e.* the nova-grain picture is not expected to produce only a simple ^{26}Al anomaly. Of course, positive δ^{26} is still expected to correlate with aluminum-rich minerals, whereas positive δ^{25} is expected to correlate with magnesium-rich minerals, so that if the original grains survived the correlations may be separable. Unfortunately, the relative yield of $^{26}\mathrm{Al}/^{25}\mathrm{Mg}$ depends on each particular nova scenario and thus cannot be predicted, although we expect larger δ^{26} anomalies than δ^{25}. It is also of interest that Lee and Papanastassiou found the largest positive values of δ^{26} to correlate with the largest δ^{18}O, as the nova-grain model predicts.

In summary, we would say that nova light curves prove that extensive grain formation is extremely rapid. A dust yield of several times $10^{-6}\,M_{\odot}$ is indicated for both opaque and transparent models. The major uncertainty in estimating the average yields of various isotopes comes from our present lack of knowledge of the range of white-dwarf compositions and of the details of envelope-dwarf mixing and ignition. Nonetheless, the suggestion that the Moon has accreted at least 10^{-6} g per gram of soil of these grains is supported by isotopic anomalies there. This small fraction of accreted soil is much less than the bulk amounts proposed by Gold (1973); but once one admits a modest amount of accretion, much larger amounts seem possible.

We thank John S. Gallagher III for bringing the ultraviolet observations to our attention and for independently communicating his measurements and interpretations to us. We also thank Robert N. Clayton for pointing our numerical errors in our lunar grain estimates. This research was supported in part by NSF grant MPS74–20076 and in part by NASA grant NSG–7015.

REFERENCES

Becker, R. H., and Clayton, R. N. 1975, *Lunar Sci.*, **6**, 32.

Black, D. C. 1972, *Geochim. Cosmochim. Acta*, **36**, 377.

Clayton, D. D. 1975*a*, *Ap. J.*, **198**, 151.

———. 1975*b*, *Nature*, **257**, 36.

———. 1975*c*, *Ap. J.*, **199**, 765.

Clayton, R. N., Grossman, L., and Mayeda, T. K. 1973, *Science*, **182**, 485.

Clayton, D. D., and Hoyle, F. 1974, *Ap. J.* (*Letters*), **187**, L101.

Clayton, R. N., Mayeda, T. K. and Hurd, J. M. 1974, *Proc. 5th Lunar Sci. Conf.*, **2**, 1801.

Donn, B., Wickramasinghe, N. C., Hudson, J. P. and Stecher, T. P. 1968, *Ap. J.*, **153**, 451.

Eberhardt, P. 1974, *Earth Planetary Sci. Letters*, **24**, 182.

Epstein, S., and Taylor, H. P., Jr. 1975, *Lunar Sci.*, **6**, 254.

Frick, U., Baur, H., Funk, H., and Signer, P. 1975, *Lunar Sci.*, **6**, 273.

Gallagher, J. S., III, and Code, A. D. 1974, *Ap. J.*, **189**, 303.

Geisel, S. L., Kleinmann, D. E., and Low, F. J. 1970, *Ap. J.* (*Letters*), **161**, L101 (GKL).

Goel, P. S., Schukla, P. N., Kothari, B. K., and Garg, A. N. 174, *Lunar Sci.*, **5**, 270.

Gold, T. 1973, *Moon*, **7**, 293.

Gray, C. M. and Compston, W. 1974, *Nature*, **251**, 495.

Grygar, J., and Hutchins, J. B. 1970, *IAU Circ.*, No. 2220.

Hoyle, F., and Clayton, D. D. 1974, *Ap. J.*, **191**, 705 (HC).

Kerridge, J. F., 1975, *Science*, **188**, 162.

Lee, T., and Papanastassiou, D. A. 1974, *Geophys. Res. Letters*, **1**, 227.

McLaughlin, D. B. 1960, in *Stars and Stellar Systems*, Vol. **6**, *Stellar Atmospheres*, ed. J. L. Greenstein (Chicago: University of Chicago Press), p. 585.

Muller, O. 1974, *Proc. 5th Lunar Sci. Conf.*, **2**, 1907.

Payne-Gaposchkin, C. 1957, *The Galactic Novae* (Amsterdam: North-Holland) p. 294.

Starrfield, S., Truran, J. W., and Sparks, W. M. 1975, *Ap. J.* (*Letters*), **198**, L113.

Starrfield, S., Truran, J. W., Sparks, W. M., and Kutter, G. S. 1972, *Ap. J.*, **176**, 169.

Yaniv, A., and Heymann, D. 1972, *Proc. 3d Lunar Science Conference*, **2**, 1967.

Donald D. Clayton: Department of Space Physics and Astronomy, Rice University, Houston, TX 77001

Fred Hoyle: Cockley Moor, Dockray, Cumberland CA 11 LG, Great Britain