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FORMATION OF GIANT H II REGIONS FOLLOWING SUPERNOVA EXPLOSIONS*

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Theoreticians are notoriously adept at cooking up schemes to explain observations, particularly in astronomy, where the parameters that go into a theory are often determined observationally only within rather wide limits. The theorist is therefore afforded considerable leeway in choosing the parameters of his model so as to match the properties of an observed object.

It is a somewhat different matter to calculate the properties of something that has not been observed. Then you have to put your cards on the table before the other fellow has shown his hand. If an object is subsequently discovered that exhibits all the properties predicted by your theory, that certainly doesn't prove the theory is right, but it does put you one up on the people whose models come after the discovery.

It was therefore with considerable satisfaction that Phil Morrison and I greeted the recent news about the Gum Nebula, since the object described by Brandt et al. (1971) is almost exactly what should surround every type I supernova remnant according to our fluorescence theory of supernova light (Morrison and Sartori 1966, 1969). Inasmuch as that theory has been more or less politely ignored by the astronomical community since we presented it a few years ago, I am going to take advantage of this opportunity to propagandize a little in its behalf. I shall first summarize the principal ideas of the theory as it pertains to the optical observations over the first few years, and then discuss the implications for the giant H II regions that are the subject of today's symposium.

The principal optical properties of type I supernovae (SN I) can be briefly summarized as follows:

i) Light curve. The photographic light curve shows a rapid rise and decline within some 10-20 days, followed by an exponential-like tail with a time constant of 50-100 days. The latter, the most reliable signature of a type I event, persists at least two years, the longest period over which a supernova

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has been followed. The decay times vary by a factor 2 or 3 between one supernova and another. The integrated energy under the photographic light curve is about 10^{49} erg.

ii) Spectrum. The spectra consist of broad bands, a couple of hundred Ångstroms wide, with very little continuum. Several of the major bands are observed to shift with time toward the red, the total shift over a few months being of order a hundred Ångstroms. The most prominent feature, which contains about half the photographic power, has its maximum around λ 4640Å in the early spectra and shifts eventually to something over λ 4700Å. The spectrum bears very little resemblance to that of a blackbody. More detailed discussion is found in many review articles. (cf.: Minkowski 1964, Zwicky 1965).

According to our theory, the observed light is principally fluorescence, excited in the medium surrounding the supernova by ultraviolet radiation originating from the explosion. The actual emission at a given point takes place over a very short interval (10-20 days or less), but the observed light at the earth is spread out over a much longer period because of the difference in total travel time for the various possible paths. If the initiating UV pulse is considered a δ-function, the locus of points seen by the observer at a given time is an expanding ellipsoidal surface (Fig. 1). The time dependence of the observed fluorescent intensity is determined by the spatial attenuation of the exciting pulse which includes a $1/r^2$ geometrical factor and an exponential factor from the absorption. In the simplest model, that of a single fluorescent line in a uniform medium, the time dependence is the exponential integral $E_1(ct/2\Lambda)$, where Λ is the mean free path for the exciting photons, i.e.:

$$\Lambda = (\sigma n)^{-1} \qquad (1)$$

where n is the density of the fluorescing material and σ the cross-section for the transition that excites the fluorescence. In the simplest version we therefore have a one-parameter theory. Figure 2 shows the fit to the measured light curves; the three cases shown include the longest-measured one, IC 4182, which constitutes the most sensitive test and ought to be included in any comparison of theoretical light curves with observations. It is clear that the E_1 function, whose asymptotic behavior is e^{-x}/x, provides a better fit than does a simple exponential, since it reproduces approximately the observed curvature in the light curve during the period 40 days $\lesssim t \lesssim$ 100 days.

I shall return to the light curves in a moment, but first I want to discuss the spectrum. The dominant photographic feature, already mentioned, is in our view He II 4686Å, the Paschen-alpha (4-3) transition. This identification is not new with us; it was suggested long ago by Minkowski. According to our geometrical picture, all the fluorescent lines are Doppler-shifted because of the (essentially) radial motion of the emitting atoms. During early times, most of the radiation observed comes from the forward part of the ellipsoid of Fig. 1; consequently the line ought to be observed as blueshifted. With time, an increasing fraction of the observed light comes from the back; the line is therefore redshifted. Thus the observed redshift of the principal features is a natural feature of the fluorescence theory.

If the observed light is principally He II fluorescence, we can calculate from eq. (1) the density of helium required to give the mean free path Λ the indicated value. The result is $n_{He^+} \sim$ 1-5 cm^{-3}. This is more helium than can reasonably be expected to be found as ordinary interstellar material, but can quite comfortably be understood as material ejected from the star during its entire pre-supernova history. The total mass of helium required for a region about a light year in radius is a tenth of a solar mass or so. The variation among measured decay times reflects, in this picture, differences in the amount of ejected helium (or its distribution).

I will not discuss the remainder of the spectrum, which is treated in our 1969 paper, and turn to the last important feature of the model. The fluorescence theory evidently demands a lot of singly-ionized helium, and we can't afford to let it lose that second electron. (The recombination time is impossibly long, and each He^+ must emit of the order of 10^5 fluorescent photons.) This requires that the spectrum that impinges on the fluorescent medium while the emission is taking place must fall abruptly across the Lyman edge of He II, i.e.: at 54 eV. (After a few days, when the fluorescence has been emitted, we don't care if the whole thing gets ionized.) Such a "filtering" action is plausibly provided by a much denser internal region, rich in helium, immediately surrounding the exploding object. This will form a Strömgren sphere during the time the intense UV pulse is passing through it. (Not to be confused with the huge fossil Strömgren sphere we are seeing today.) The optical depth for ionizing photons is very great, and recombination is rapid. An appreciable fraction of the recombinations takes place to excited states, each such event effectively converting an ionizing photon into two or more photons below the edge. This is what happens in ordinary H II regions, planetary nebulae, etc., which filter out all radiation above the hydrogen Lyman edge.

The amount of material required to accomplish the desired filtering in the SN I case, calculated with the formulas that apply to static Strömgren spheres, is a few tenths of a solar mass. Obviously the conditions inthe region we have in mind are very different from these in a classical Strömgren sphere. The energy input is very intense and very brief, and one does not even know the form in which the primary energy arrives; it could, for example, be carried by particles.

Nonetheless the simple estimates suffice to convince us that the filtering action can occur. This aspect of the problem must be looked at in greater detail.

The dense region serves one other purpose – it slows down the photons below the edge by Thomson scattering, thereby spreading out the UV pulse in time. Even if the initial pulse was very short, a characteristic time of order 10 days is produced by this mechanism, without appreciably altering the spectrum. With a diffusion-broadened input of this nature, the divergence at $t = 0$ in the light curve calculated with a δ-function input is removed, and the early part of the light curve is in fact quite accurately reproduced. Figure 3 shows a composite of the light curves of six SN I, plotted as a function of t/Λ, where Λ is obtained from the late-time behavior. The universality of the SN I phenomenon is strikingly demonstrated by this plot, and the fit provided by the two-parameter version of the fluorescence theory is seen to be quite good. We wish to emphasize, however, that whereas the filtering action of the dense region is absolutely essential to the theory, the time diffusion is not. The pulse could be broadened by some other mechanism; or the early luminosity could contain a substantial non-fluorescent contribution.

A number of other details of the theory are discussed in our paper. The feature of interest here today is of course the ultraviolet radiation which the theory implies, and the ultimate effect of these UV photons in producing the Gum Nebula. The energetic argument is quite straightforward. Each 3-volt photon from the He II 4-3 transition requires a 50-volt photon to excite the initial state. When one takes into account the rather small fluorescent yield for the transition in question, the over-all conversion efficiency (output visible energy/excitation UV energy) turns out to be about 1/200. With an integrated measured energy in the dominant 4686Å feature of about 5×10^{48} erg, this implies about 10^{51} erg of excitation energy, concentrated in a band a few eV wide in the vicinity of 50 volts. We have no idea as to the detailed shape of the primary spectrum, but can hardly expect all the energy to be concentrated in so narrow a band. Assuming that the fraction of photons in the excitation band is of order 10%, we arrived at 10^{52} erg as our estimate of the total UV energy incident on the fluorescent medium. If you like, you can say that the bolometric correction for this unusual emitter is some eight magnitudes! The bulk of the energy is found in the form of He II Lyman-alpha radiation ($h\nu = 40$ eV), He II Balmer lines, and continuum below 54 volts.

What happens to all these UV photons? A few of them make the observed fluorescence. But the majority (including all the He II Lyman-alpha) escape from the neighborhood of the supernova and ionize the surrounding gas as far as they can reach. That is to say, they make a Gum Nebula. Our estimate of 10^{52} erg implies about 10^{62} photons, which make an equal number of ions.

This is just about the number deduced by Brandt et al. from the observations. The numerical agreement is closer than we have any right to expect, but it seems fair to say that the predicted extent of the ionized region is consistent with the observations on the Gum Nebula.

The H II region formed by this mechanism is initially quite hot. When a He II Lyman-alpha photon ionizes a hydrogen atom there is 27 eV of kinetic energy left over; thus when the system comes to thermal equilibrium the temperature will be ≈ 9 eV or roughly 10^5 °K. The system will then cool gradually and expand. The time evolution of such an object is discussed by Kafatos (1971).

At least two other mechanisms for the production of the ionization in the Gum Nebula have been proposed. Tucker (1971) considers the shock wave associated with the expansion of the supernova shell, and argues that this will eventually radiate copiously in the UV. By an appropriate choice of parameters, he can get enough UV to ionize the nebula.

The other idea, due to Ramaty et al. (1971), is that the nebula is ionized not by radiation but by collision with heavy particles, of energy ~10 MeV, ejected in the supernova event. The production of these particles is a consequence of Colgate's theory of the explosion (Colgate and McKee 1969, Colgate 1971).

I shall not give a detailed critique of the competing theories, but I do wish to make a few general remarks. The first one is this: The Morrison-Sartori theory deals exclusively with the post-explosion supernova. We recognize that many of the most interesting phenomena take place earlier, as the pre-supernova rushes through the final states of its evolutionary track. The period before and during the explosion has received much theoretical attention, and deservedly so. But the calculations involve many assumptions and are very complicated; unfortunately the results are not subject to direct observational test. Our theory, on the other hand, is very simple (in fact, surely oversimplified), but it can be tested observationally and seems to pass every major test. When the simplest version of a theory, with very few adjustable parameters, accounts for the principal features of a phenomenon, one is encouraged to believe that it forms the basis for the correct explanation. This does not mean the model is correct in every detail.

When we first proposed the fluorescence theory, our estimate of 10^{52} erg of ultraviolet energy was held to be excessively high. Colgate (1971) argues on the basis of hydrodynamic calculations, that the UV we require cannot possibly be produced in the explosion. We find such an argument unconvincing, because it rests on assumptions for which there is no observational evidence. We take the point of view that the observed properties of the post-explosion object (among which the Gum Nebula now plays a prominent role) strongly suggest that at least

10^{52} erg of UV is indeed produced. If the hydrodynamic model cannot come up with the required energy, perhaps the supernova is even more clever.

Incidentally, we are quite willing to concede comparable amounts of energy to cosmic rays, to kinetic energy of expansion, shocks, flywheel mass loss, or other channels. We see no reason why a total energy release several times 10^{52} erg should be considered unacceptable ($1 M_{\odot} c^2 = 2 \times 10^{54}$ erg).

The principal difference between an ionized region produced by our mechanism and one produced à la either Tucker or Ramaty et al. is the time scale for production. Our Strömgren sphere is produced instantaneously – the ionization front expands at essentially the speed of light. Both of the other mechanisms require much more time; according to them, the Gum Nebula is a newly-formed object. In fact, if the age is $\sim 10^4$ years there is some difficulty in ionizing the outer parts on the cosmic-ray hypothesis.

An obvious means for investigating the formation time is to look at a young supernova remnant. The best candidate is Tycho, 400 years old, and identified as SN I on the basis of evidence which is suggestive although not conclusive. If Tycho is indeed a SN I, its "Gum Nebula" should already have formed, according to our picture, whereas according to the others the ionization is just getting started. Unfortunately, even if Tycho were a fully formed Gum Nebula it would be a far less spectacular object. In the first place it is much further away ($\sim$5 kpc). Moreover, being 100 pc out of the plane, the gas density in the vicinity of Tycho is fairly small which would make its emission measure very low unless some clouds were included. And at an age of 400 years, the nebula would still be very hot, making it very hard to observe in H-alpha, although some forbidden lines may be observable. (See Kafatos 1971.)

Some very tentative evidence for the presence of an ionized sphere around the Tycho remnant is provided by the observation of a "hole" in the 21-cm emission (Williams 1971) just at the position of the supernova. Unfortunately, many such holes are found in places where no known supernova remnant resides, so the evidence is far from convincing. It may be, however, that this undramatic sign is the only one by which such a young and distant Gum Nebula identifies itself.

All the ideas presented here have been developed jointly with my collaborator, Philip Morrison. Conversations with Minas Kafatos have been very useful.

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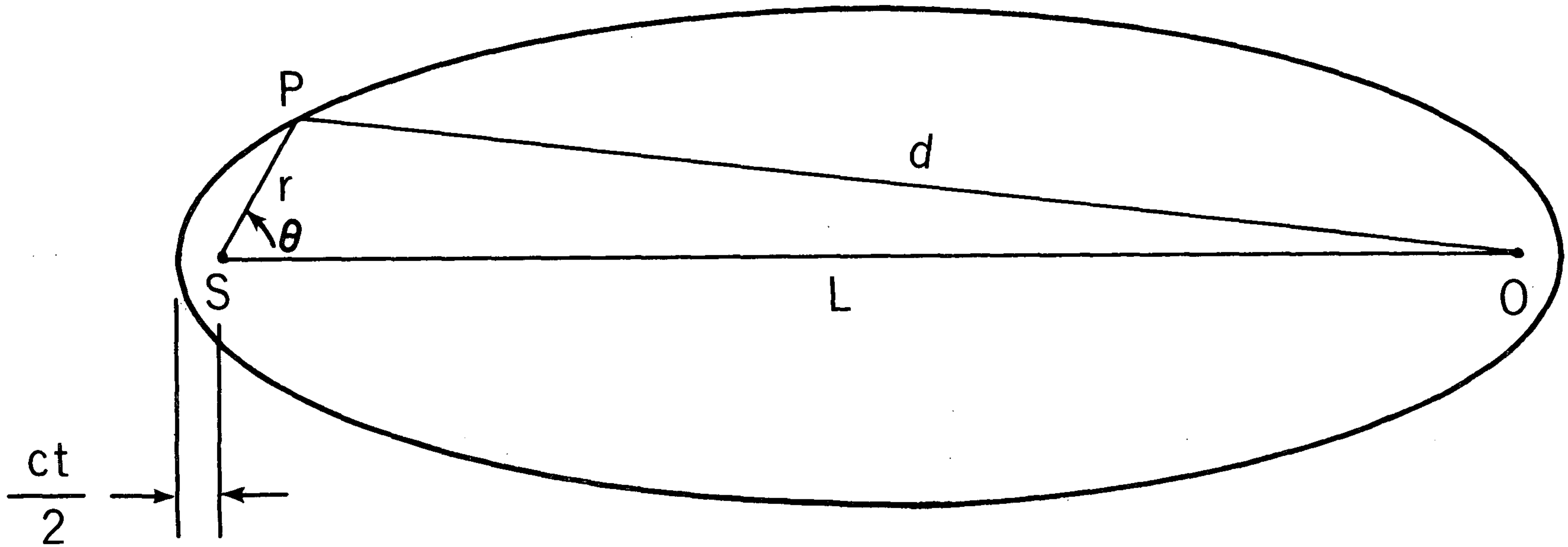

Figure 1. Locus of points from which fluorescent emission reaches observer O at a given time t, for a δ-function pulse originating at S; t is measured from the arrival time of the direct signal, i.e.: from time L/c after the explosion. The surface is an expanding ellipsoid, given by $r + d = L + ct$. (From Morrison and Sartori 1969, published by the U. of Chicago Press. Copyright 1969 by the University of Chicago. All rights reserved.)

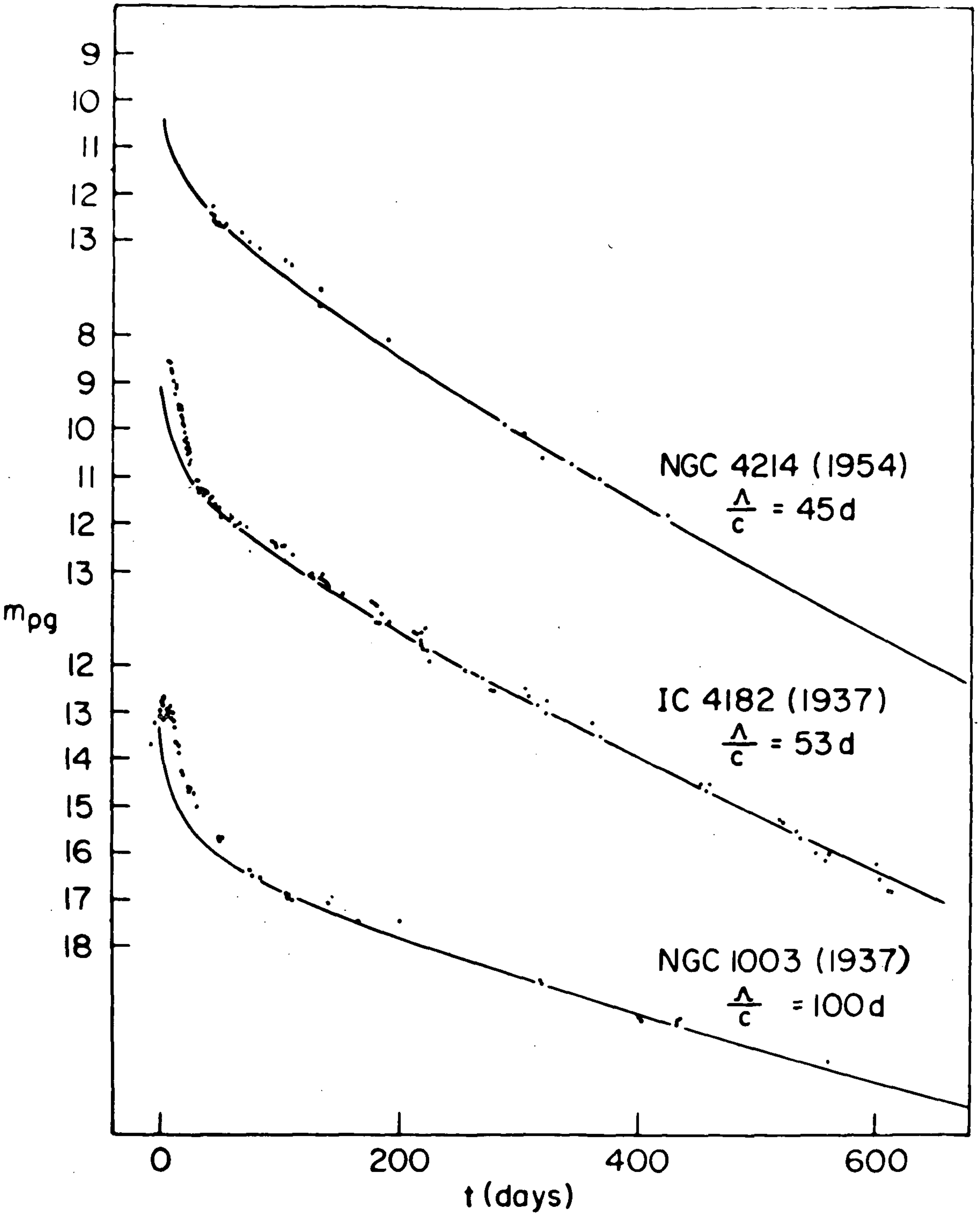

Figure 2. Theoretical fit (on the basis of the model with uniform density, δ-function excitation pulse, and a single absorption line) to the photographic light curves of type I supernovae in three galaxies. The parameter Λ/c in the luminosity function, $L(t) \sim E_1\ (ct/2\Lambda)$ is shown for each light curve. (From Morrison and Sartori 1969, published by the U. of Chicago Press.)

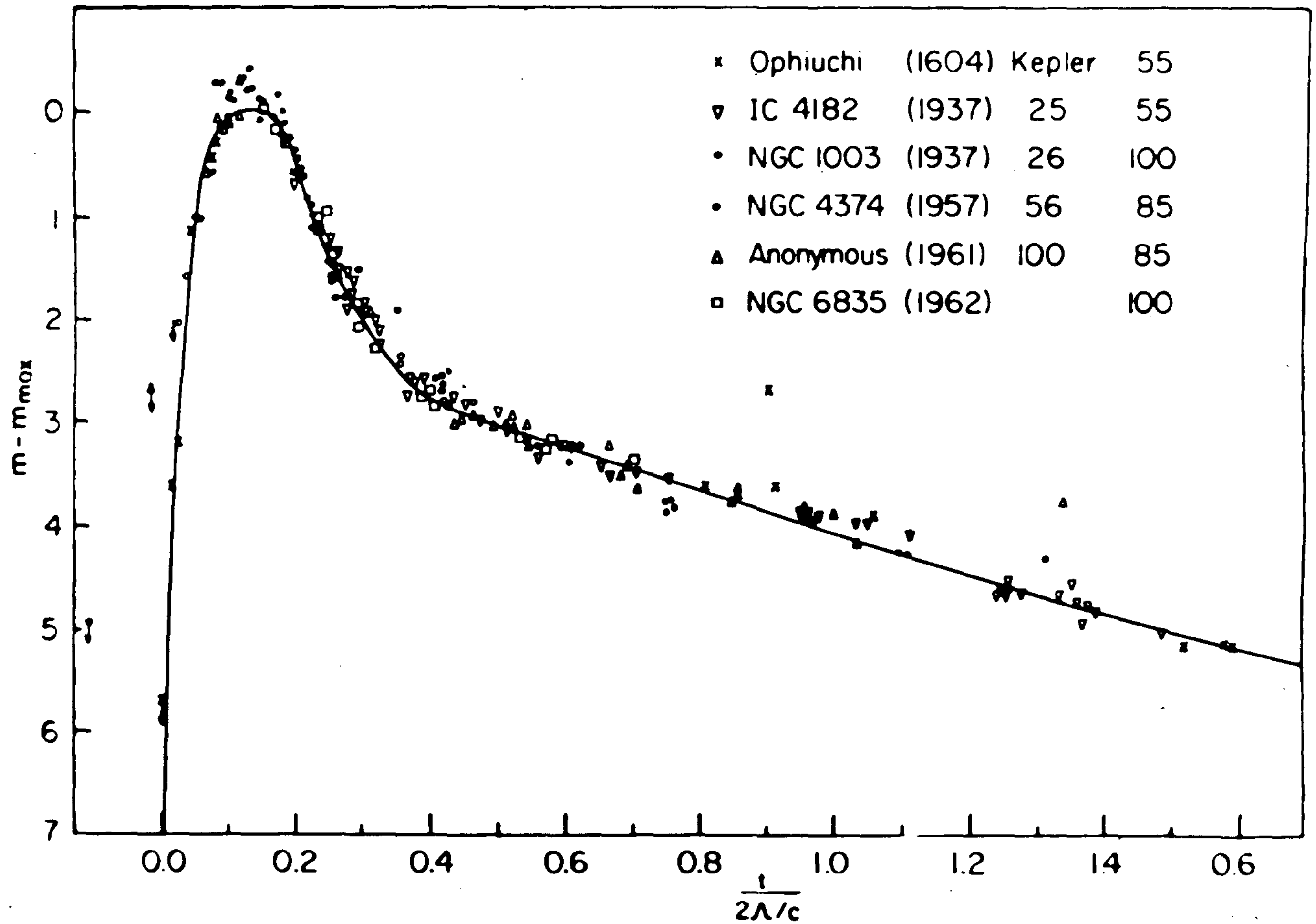

Figure 3. Composite photographic light curve for type I supernovae. The luminosity is plotted as a function of the dimensionless variable $\frac{1}{2}$ ct/Λ. The name, date, Zwicky Number (where applicable) and Λ are given for each supernova. The points for Kepler's supernova are from visual observations, but they probably include a substantial amount of the 4600 Å radiation that dominates the photographic light curve of a SN I. (From Morrison and Sartori 1969, published by the U. of Chicago Press. Copyright 1969 by the University of Chicago. All rights reserved.)

DISCUSSION

A. G. W. Cameron: It seems to me that there are many supernova light curve theories that would predict a great deal of ultraviolet emission, so the discovery of a fossil Strömgren sphere is not necessarily evidence for your theory. One should attempt rather to argue in reverse. That is, are there features of the Gum Nebula which specifically yield more information than just that there was an ultraviolet burst.

S. A. Colgate: [Dr. Colgate gave the arguments against great ultraviolet emission from a supernova that he presents in detail elsewhere in this volume. – Editor.]

A. G. W. Cameron: Dr. Colgate has not included the pulsar, which should have 10^{52} erg in rotational energy initially, which it will shed in a time scale comparable to that of the supernova light curve.

L. Sartori: It seems more appropriate to start from our deduction (for the Gum Nebula) that 10^{62} ultraviolet photons were produced by the supernova, and to place this as a condition on supernova theories, than to argue on purely theoretical grounds that 10^{62} ultraviolet photons cannot be produced.

T. L. Page: What are the requirements of your theory as to the production of helium in the pre-supernova evolution?

Sartori: About 0.1 solar mass has to be produced over the stellar lifetime and diffuse out to a distance of about one light year. It need not happen only in the last stages of evolution. The uniform helium distribution that we have assumed represents a zero order model, but it is not necessary to have a strictly uniform helium density in order to get good agreement with the light curve.

A. Poveda: The observations of bright supernovae, when a reasonable bolometric correction is made, do not imply more than 5×10^{50} erg in radiation.

Sartori: According to our view, the spectrum is completely unlike that of a blackbody and the bolometric correction is 8 magnitudes. In the optical wavelengths, the observed spectrum has strong emission bands and does not resemble a blackbody.

D. Reames: Does the Doppler-shift interpretation require that the material be moving radially before the photons get to it?

Sartori: The theory is consistent whether the material is already in motion or not, for velocities less than 0.01 or 0.02 times the speed of light.

D. P. Cox: The mean free path is only one scattering; is that correct?

Sartori: The simple version of our theory, in which we get good agreement with the light curve, takes only a single fluorescence into account. If we wish to include the effects of multiple scattering, the mathematical problem becomes much more complicated. It is not obvious how the light curve would be affected. Any effect of secondary fluorescence will be delayed with respect to the first one.