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HIGH EXPLOSIVE SIMULATIONS OF SUPERNOVAE AND THE SUPERNOVA SHELL FRAGMENTATION MODEL OF SOLAR SYSTEM FORMATION

by

Wilbur K. Brown

ABSTRACT

Comparison of photographs of explosive experiments to the Casseopeia A supernova remnant reveals a striking similarity. The similarity could indicate the presence of a relatively cool, underlying shell in the Casseopeia A remnant. As this shell expands and fragments, the observable features are produced by hot gases squirting through the cracks—as in explosive experiments. The existence of such underlying shells in supernova remnants supports the author's model of solar system formation.

I. INTRODUCTION

My colleague, L. A. Gritz, and I have recently published (Brown and Gritz 1986) a modern version of my original solar system formation model (Brown 1970, 1971). This model postulates fragmentation of a shell ejected from a type II supernova (SN II) and yields mass distributions in the resulting solar nebulae: a separate solar system is presumed to be formed from each fragment. This model produced mass distributions much like those of our solar system over a wide range of model parameters (Brown and Gritz 1986), and a further search of the parameter space of the model yielded predictions of mass distributions in the solar nebulae of solar systems as yet undiscovered (Brown 1987).

If the expelled supernova shell fragments are injected into a pristine region of a molecular cloud, each fragment will sweep up additional mass, a process that will lead to a local condensation due to the gravitational instability caused by the fragment mass. Such newly formed stars may already have been observed (Herbst and Assousa 1977, Assousa et al. 1977). The new stars may, in turn, end their lives as supernovae in a chain-reaction mechanism that is a variant of the stochastic self-propagating star-formation theory advanced by Seiden (1983). I have called this cascade "sequential fragmentation," and my model of it (Brown 1986) produces a one-parameter initial mass function that is quite realistic. Because the gas density in a young galactic disk probably decreases with galactic radius, I assume ejected shell fragments (which would have masses $\lesssim 10^{31}$ g) would sweep up less mass the further out in the galactic disk their supernova progenitor occurred. Thus, based on the present model, I would expect the galactic dark matter to be solid baryonic bodies: brown dwarves, Jupiters, and smaller bodies (see the constraints presented by Hills [1986]). The mass fraction of these bodies would increase with galactic radius.

Later in this report, I will present photographs of the breakup of an explosively driven spherical shell for which the apparent phenomenology bears a striking resemblance to that of the Cassiopeia (Cas A) supernova remnant (SNR). The resemblance may indicate the presence of a relatively cool, fragmented, underlying shell in the Cas A SNR—like the shell present in the explosive experiments. The existence of such a shell in the Cas A SNR (and other type II SNRs) would lend support to my model of solar system formation.

II. THE MASS DEFICIT IN THE CRAB NEBULA

According to our present knowledge of the presupernova star and the observed remnants, the Crab Nebula appears to have a mass deficit. In her excellent review of the supernova literature, Trimble (1982, 1983) includes a statement of the Crab Nebula mass deficit problem: roughly speaking, the mass of the presupernova star must have been about $9 M_{\odot}$, whereas the mass of the filaments is perhaps $1 M_{\odot}$, and that of the pulsar, $2 M_{\odot}$. The following discussion considers each of these values.

Arnett (1975) made the first effort to estimate the mass of the precursor star to the Crab Nebula and based his calculations on the need to have the precursor produce significant amounts of helium (but very little of the heavier elements). The present commonly accepted value is $8-9.5 M_{\odot}$ given by Nomoto (1982) and Nomoto et al. (1982). Other pertinent articles include Woosley et al. (1980), Miyaji et al. (1980), Murdin and Clark (1981), Hillebrandt (1982), Nomoto (1985), and Henry (1986).

Davidson and Tucker (1970) gave the mass in the Crab filaments as $1.45 M_{\odot}$. Davidson later mentioned a possible filament mass of $2 M_{\odot}$ or even $3 M_{\odot}$ (Davidson et al. 1982, Davidson 1985), but I have not been able to substantiate these higher values. Murdin and Clark (1981) also mentioned this apocryphal value of $2-3 M_{\odot}$. Henry and MacAlpine (1982) gave a more firm number for the filamentary mass— $1.2 M_{\odot}$. The Crab Nebula is so young that it cannot have swept up much additional interstellar mass. I adopt the range $1.2-2 M_{\odot}$ for the Crab filamentary mass.

The mass of the Crab pulsar is often assigned a rough value of $1.44 M_{\odot}$, i.e., the Chandrasekhar limit. Weinberg (1980) derived a theoretical mass of $2 M_{\odot}$ for the pulsar. Hillebrandt (1982) calculated a neutron star mass of $1.44 M_{\odot}$ from the supernova explosion of a $10 M_{\odot}$ star. I adopt a range of $1.44-2 M_{\odot}$ for the Crab pulsar.

A presupernova star mass of $8-9.5 M_{\odot}$, a filamentary mass of $1.2-2 M_{\odot}$, and a pulsar mass of $1.4-2 M_{\odot}$ obviously do not account for all the original mass. Table I lists this mass deficit for the Crab Nebula. The deficit lies in the range of $4-6.9 M_{\odot}$ and must somehow be explained.

There are several explanations, or partial explanations, for the mass deficit in the Crab Nebula. One possibility is that the presupernova star may have lost mass through wind episodes during a supergiant stage (Conti and McCray 1980, Maeder 1981, Morris and Zuckerman 1986). Murdin and Clark (1981) have presented evidence that the Crab Nebula may have a massive halo of $\approx 5 M_{\odot}$. (See also Mauche and Gorenstein [1985].) Other mechanisms could be gravitational radiation from the imploding and exploding supernova or radiation of massive neutrinos. I find these explanations unsatisfactory, and I suggest that the missing mass is there in the supernova remnant but not directly detectable. In 1970 I proposed that massive fragments of any supernova shell would be propelled outward by the explosion, whereas the hot gases would squirt through the cracks (Brown 1970). Shortly afterward, Davidson and Tucker (1970) suggested that there might be relatively cold, neutral "cores" within the Crab filaments and that the mass of these cores might be substantial. I estimated (Brown 1970) that the minimum mass necessary to form the planetary disk of our solar system from supernova shell fragmentation would be 2550 Earth masses, or $\approx 10^{-2} M_{\odot}$. The mass deficit of Table I would be adequate for the formation of multiple solar systems like ours.

Table I. The Crab Nebula Mass Deficit

Quantity	Range	Low Deficit	High Deficit
PreSN Star($M_{\odot}$)	8—9.5	8	9.5
Filaments($M_{\odot}$)	1.2—2	2	1.2
Pulsar($M_{\odot}$)	1.4—2	2	1.4
Deficit ($M_{\odot}$)	—	4	6.9
Total Mass/Detectable Mass	—	2	3.7

If stars are usually formed through stochastic self-propagating star formation (Seiden 1983) according to my sequential fragmentation scheme (Brown 1986), and if the Crab Nebula is typical, then we can see from Table I that the local mass/luminosity ratio in the galactic disk could easily be in the range 2.3-3.3 (Faber and Gallagher 1979). I note that there also is an energy deficit in the Crab Nebula (and other SN II) and that it does not seem possible to explain the energy deficit with the undetected mass proposal.

Building upon the evident mass deficit of the Crab Nebula, I assume that such a deficit exists in other SNRs, particularly in the Cas A remnant.

III. SUPERNOVA MOCKUP EXPLOSIONS

It may be possible to simulate an SN II explosion on the laboratory scale. According to the scenario presented above, a centrally detonated sphere of high explosive surrounded by a spherical steel shell would serve as a mockup. The spherical shell of steel would simulate the relatively cool ejected supernova shell (including the heavy elements) as it expands and fragments.

Figure 1 is a high-speed photograph taken some years ago of an explosive experiment configured as described above. Note the scalloped appearance of the incandescent gases as they pass outward through the cracks between the polygonal fragments of the expanding steel shell. According to the present theory, these fragments—underlying the hot gases—represent the undetected mass of supernovae. Figure 2 is another, more recent high-speed photograph of a similar explosive experiment. Again, note the scalloped appearance of the escaping hot gases. In both of these explosive experiments, the underlying steel shell, although shocked, remained relatively cool.

Fig. 1. A high-speed photograph of a homogeneous metal shell driven outward by the detonation of a structureless high explosive within. Incandescent gases have passed outward between the metal fragments and have given rise to the scalloped appearance. A mirror, positioned above the explosion at 45° , affords a view from the top. The unusual phenomenon at the top, which is due to special conditions of this particular experiment, is not pertinent and should be disregarded. (≈ 1969 Los Alamos Scientific Laboratory photograph obtained from J. Don Harper.)

Fig. 2. A high-speed photograph similar to Fig. 1. Note the scalloped appearance of the incandescent gases as they squirt between the underlying metal shell fragments. (1984 Los Alamos National Laboratory photograph of explosive experiment No. 3434 obtained from Mike Christian.)

IV. CAS A

Figure 3 is a radiograph of Cas A taken at 5 GHz. Cas A is the remnant of an SN II that occurred circa 1658. The remnant shown in Fig. 3 displays the same scalloped look as do the two explosion photographs shown in Figs. 1 and 2. I claim that the knots and filaments that constitute the scalloped pattern of the gases of Cas A are caused by these gases squirting out between the underlying, relatively cool fragments of the supernova shell ejected in the 1658 explosion. When the Cas A remnant of Fig. 3 is compared with the explosion photographs of Figs. 1 and 2, the evidence seems to substantiate my claim.

The explosive experiments shown in Figs. 1 and 2 were not originally carried out to simulate supernovae events. Therefore, I think that dedicated explosive experiments deliberately planned to mock up supernovae would improve the comparison. Theoretical analysis supporting such experiments might yield scaling laws and improvement of experimental designs. For example, if nested, concentric shells of varying density and thickness surrounded the high explosive, the simulation of supernovae might be more realistic. Theoretical analysis, computational support, and explosive experimentation in simulating supernovae would take advantage of the unique capabilities of the Los Alamos National Laboratory.

V. CONCLUSION

I have pointed out the obvious similarity between the photographs of two explosive experiments and the Cas A SNR. Because the explosive experiments featured the passage of hot gases out through the cracks between the fragments of the underlying spherical shell, I conclude that the Cas A remnant is also a manifestation of an invisible, fragmented, relatively cool shell underlying the Cas A SNR gases. The appendix presents a model of the rising front edge of the light curve. The existence of the mass deficit of the Crab Nebula strengthens the fragmentation hypothesis and supports my concept of solar-system formation from supernova shell fragments.

Finally, as a bit of whimsy, I include Fig. 4, a photograph of a seed ball from a common flower, for comparison with the previous figures.

Fig. 3. A radiograph of the Cas A SNR showing the knots and filaments. I believe that the scalloped appearance is a signature of a fragmented, relatively cool supernova shell underlying the observed gases. (1978 Mullard Radio Astronomy photograph by Steve Gull and the staff of the 5-km University of Cambridge radiotelescope. Reprinted by permission.)

Fig. 4. A photograph of the seed ball from Yellow Salsify *Tragopogon dubius*.

APPENDIX

LIGHT TRANSMISSION THROUGH THE FRAGMENTED SHELL

Hydrodynamic fragmentation of the supernova shell would mean that in the explosion, the ejected shell would expand until the tension exceeds the strength of the material at the breakup radius R_b at time t_b . If the size of the relatively cool, opaque fragments remains the same for $t > t_b$, then the transmission of light, T , from behind the shell, $R > R_b$, is given by

$$T = \frac{4 \pi R^2 - 4 \pi R_b^2}{4 \pi R^2} = 1 - \left(\frac{R_b}{R}\right)^2. \quad (A1)$$

The relationship between radius and time is attributed to J. Von Neumann:

$$R = at^\beta, \quad (A2)$$

where the power β is equal to $2/5$ in the usual Sedov (1959)–Taylor (1950a, b) scaling. When Eq. (A2) is written for the breakup radius and divided into Eq. (A2), I obtain

$$\frac{R}{R_b} = \left(\frac{t}{t_b}\right)^\beta. \quad (A3)$$

This means one may consider the radius as measured in units of R_b and the time in units of t_b ($t/t_b \geq 1$).

When Eq. (A3) is substituted into Eq. (A1), I obtain

$$T(t) = 1 - \left(\frac{t}{t_b}\right)^{-2\beta}. \quad (A4)$$

Whereas expansion into a rarified medium is described by $\beta = 2/5$, for underground nuclear explosions the appropriate value of $\beta \approx 1/2$. (This is the crux of the CORTEX method of measuring the energy yield of underground nuclear explosions.) Using the latter value, I find from Eq. (A4) that

$$T(t) \approx 1 - \left(\frac{t}{t_b}\right)^{-1}. \quad (A5)$$

For example, at a time of $t/t_b = 10$, Eq. (A5) indicates a transmission of 90%.

The light curve of an SN II would be given by

$$L(t) = L_o T(t) f(t), \quad (A6)$$

where $f(t)$ is a possibly complex but monotonically decreasing function of time depending on the decay of various isotopes produced in the explosion. The constant L_o is a luminosity proportional to the light-producing energy yield of the explosion. If, for example, the light generated by decay of these isotopes is at first dominated by ^{56}Ni ($\tau = 8.8$ days), then

$$L(t) = L_o [1 - \left(\frac{t}{t_b}\right)^{-1}] e^{-t/\tau} \quad (A7)$$

would describe the early time-dependent luminosity in this simple case.

Further, I may obtain the velocity, $\dot{R}$, from Eq. (A2):

$$\dot{R} = \beta R t^{-1}. \quad (A8)$$

Assuming that the presupernova star was a red giant, I substitute the following guesses into Eq. (A8) for the values of R and t at the moment of breakup:

$$\begin{aligned} R_b &= 100 R_\odot \quad (R_\odot = 7 \times 10^5 \text{ km}) \\ t_b &= 1 \text{ day} \\ \beta &\approx \frac{1}{2}. \end{aligned}$$

I obtain $R = 400 \text{ km/s}$ for the relatively cool, opaque shell. The shell fragments may be identified with the quasi-stationary flocculi (QSFs) in, for example, the Cas A SNR (Raymond 1984). In contrast, the gases that squirt out through the cracks between the fragments and continue outward to produce the filaments of the SNR are moving at 5,000–15,000 km/s (Trimble 1982, 1983). It seems clear that it would be more difficult to accelerate the relatively massive fragments of a supernova shell than it would be to accelerate the gases that squirt out between the fragments.

When sufficient early-time supernova light-curve data become available, the present theory of $T(t)$ may be tested against reality.

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