Life (Briefly) Near a Supernova

Steven I. Dutch

Natural and Applied Sciences, University of Wisconsin-Green Bay, Green Bay, WI 54311-7001, dutchs@uwgb.edu

ABSTRACT

Supernova explosions are so enormous that their scale is difficult to imagine. Thought experiments and simple calculations involving the Sun going supernova can help with visualization. The energy flux would be roughly equivalent to having the entire earth's nuclear arsenal detonated a kilometer away, and would be sufficient to boil away the surface at hundreds of meters per second. Even on the temporarily protected night side, scattered light in the atmosphere and light reflected from interplanetary dust would far exceed normal sunlight, and radiation reflected from the moon would heat the earth to lethal temperatures if the moon were near full. The earth would take at most a few days to vaporize. Fortunately, the sun is not massive enough to become a supernova. Supernova explosions occur only in short lived stars, so that the melancholy science fiction theme of a civilization being incinerated by its own sun is very unlikely to happen in reality.

INTRODUCTION

Before the Wisconsin ice advance, before the Sangamon interglacial, while the Illinoisan ice sheets still covered much of North America, an aged star in the Small Magellanic Cloud collapsed and exploded. It took until 1987 for the light to reach the Earth. Across 170,000 light years, this single star was as bright as the stars in the Big Dipper. It was the first supernova visible to the unaided eye since the invention of the telescope (Arnett and Others, 1989).

Supernovas are among the most violent events we witness in the Universe. For a few days, a single star puts as much energy as the rest of its galaxy combined. Most types of supernova occur in binary star systems when a companion star accretes matter from a larger neighbor, suddenly collapses gravitationally and begins a new cycle of fusion reactions (Arnett and others, 1989; Marschall, 1988; Murdin, 1990; Wheeler 2000). The sudden burst of energy blows off the outer layers of the star. Novas, a less violent type of stellar explosion, also always involve binary star systems. In novas, matter accreting onto a white dwarf from a neighboring star becomes dense and hot enough to undergo nuclear fusion on the surface of the white dwarf.

However, one variety of supernova, the type II supernova, occurs when massive single stars reach the end of their life cycles. After the hydrogen in their cores is exhausted, the core collapses until a new cycle of reactions fuses helium to carbon. Later cycles create oxygen, silicon, and finally iron. The core of the star assumes a shell structure with the residue of one fusion process providing the fuel for the next, until the end product, iron, results. It would seem that the shells could grow outward, each supplying fuel for the one inside it, until the star eventually consisted entirely of iron. However, the iron core soon becomes too massive to withstand its own gravity, and fusion of heavier

pressure that resists collapse. In milliseconds the core collapses to a neutron star (or in extreme cases, a black hole). The rest of the star falls inward onto the neutron star, which may have the mass of the Sun but a radius of only a few kilometers. The gravitational attraction of the neutron star core accelerates the infalling matter to perhaps ten per cent of the speed of light. Up to several times the mass of the Sun plows into a neutron star at a tenth of the speed of light and the results, to put it mildly, are impressive. During the collapse, nuclear reactions run riot and the energy outburst blasts off the outer layers of the star. We look straight into the thermonuclear core of the star.

To get across to students the staggering violence of a supernova explosion, I have developed a few analogies that I present here. The purpose of this paper is to present a few simple analogies that I have found more effective and accessible than the standard textbook comparison that the supernova outshines the rest of its galaxy. A galaxy, after all, is a rather remote concept; picturing the world's nuclear arsenal detonating a kilometer away is both vivid and sobering. An additional purpose is to suggest possible avenues for developing quantitative exercises, ranging from simple to moderately complex, that instructors may wish to pursue.

The Sun is not massive enough to become a supernova, because it can never achieve the high densities and temperatures needed to create elements heavier than carbon. Nevertheless, the dramatic possibilities of such an event are simply too grand for science fiction authors to ignore. Many science fiction stories (including the three discussed in this paper) are predicated on the assumption that the stellar catastrophe occurs almost instantly and that planets around the doomed star remain livable until shortly before the final disaster. Indeed, the collapse of the star's core does happen in milliseconds. However all supernovas are thought to occur in stars that have exhausted their initial hydrogen and gone on to fusion of heavier elements. Such stars would be in the red giant phase. The precursor star to the 1987 supernova initially challenged this assumption, in that if appeared before the explosion to have been a normal blue-white supergiant. However, it is now believed that the star was an aging red giant that had shed nearly all of its outer envelope so that the hot core of the star was showing through (Arnett and others, 1989; Murdin, 1990). Evolution of a star to the red giant phase will likely result in extinction of life in the star's habitable zone, so that the frightening prospect of a benign sun suddenly exploding is extremely unlikely.

SOME ESSENTIAL DATA

However, for pedagogical purposes we can pose the thought question: what would it be like if the Sun suddenly went supernova? Besides, there's always the possibility that we've missed something in our theoretical understanding. For reasons that will soon become obvious, the calculations need not be overly precise and most figures are cited to one or two digit elements absorbs energy, shutting off the radiation accuracy. Most of the numerical data are taken or

Dutch - Supernova 27

derived from Ahrens (1995) and Lodders and Fegley How bright is 10 billion times solar luminosity? The (1998). Descriptions of nova and supernova processes can be found in Arnett and others (1989), Marschall (1988), Murdin (1990), Wheeler (2000), or indeed any modern astronomy text. Most of the necessary formulas are in Lodders and Fegley (1998) and other standard physics and chemistry texts. First, a few basic facts:

- Absolute magnitude of the Sun (brightness as seen from 10 parsecs or 32.6 light years): 4.8
- Energy output of the Sun: 3.9 x 10 ²⁶ joules/sec
- One megation: 4.2 x 10¹⁵ joules (Glasstone and Dolan, 1977)
- Absolute magnitude of a typical Type II supernova: -20 to -22
- Brightness ratio of two stars differing by M magnitudes: 100M/5 or 2.512M
- Distance from Earth to Sun: 1.5 x 108 km
- Apparent magnitude of the Sun: -26.8
- Apparent magnitude of the full Moon: -12

From the data above, a typical supernova outshines the Sun by at least 10 billion times. We will use the figure 10 billion, the order of magnitude used in most texts, which translates conveniently to 25 magnitudes of brightness. Across 32.6 light years (ten parsecs), the defining distance for absolute magnitude, a typical supernova would still be 0.1 percent as bright as the Sun and 1600 times as bright as the full Moon.

A SCALE MODEL APPROACH

Even the cosmically modest energy output of the Sun is still too huge to imagine, let alone that of a Sun gone supernova. So one approach to making the quantities comprehensible is to scale things down a bit. What would it take to produce the radiation flux of the sun at a distance of one kilometer? In thermonuclear terms, the Sun generates about 90 billion megatons a second. A megaton is the energy equivalent of a million tons of high explosive (incidentally, for purists about units, I have never seen an application of kiloton or megaton energies where it made the slightest difference whether the tons were short or metric). What would produce the equivalent energy flux at a distance of one kilometer? The answer is easy: 90 billion (energy output in megatons) divided by 150 million (Earth-Sun distance in kilometers), squared. The result is 4 x 10⁻⁶ megatons, or 4 tons of explosive per second. 90 billion megations is hard to relate to, but it's not hard to picture a few tons of high explosive (say a truck full) or an exploding gasoline tanker a kilometer away giving off a burst of light and heat that would briefly rival the Sun.

Now imagine the Sun going supernova and brightening by a factor of 10 billion. The scaled down energy output increases by ten billion times to about 40 billion tons or 40,000 megatons per second. The total energy of the Earth's nuclear arsenals is on the order of a few tens of thousands of megatons (EFNS, 2002). The sun going supernova would be the equivalent of standing a kilometer away when the entire Earth's nuclear arsenal goes off every second. And this radiation flux would go on for several days, before dropping to a plateau of "only" a billion times solar luminosity for roughly 100 days. Clearly, the Earth would not survive.

LIGHT AND HEAT

visible sky has an area of 20,626 square degrees, and the Sun has an apparent area of 0.2 square degrees. It would take 100,000 Suns to cover the visible sky. Imagine the entire sky covered with Suns. Now imagine each of them 100,000 times brighter than our Sun. You could never see anything this bright. Your light receptors would overload instantly and you would probably vaporize before the sensory input could reach your brain. Very likely the flux of penetrative (X-ray and gamma ray) radiation would be enough to disrupt every atomic bond in your body before the sensory input could reach your bråin.

How hot would it get? The Stefan-Boltzmann Law holds that radiation is proportional to the fourth power of temperature, or conversely that temperature is proportional to the fourth root of radiation flux. Right now the mean temperature of the Earth is about 270 K, just below the freezing point of water. (Earth is warmer because of the natural greenhouse effect of water vapor and carbon dioxide. As the late Carl Sagan put it, a little greenhouse effect is a good thing.) If the Sun brightened by 10 billion times, the temperature on Earth would increase by the fourth root of that figure, or about 316 times, to 85,000 K. This is roughly 15 times hotter than the present surface of the Sun and far above the boiling point of any known material. The Earth would indeed vaporize.

Could any planet survive a supernova? In his short story The Star (Clarke, 1959), Arthur C. Clarke described a voyage to a supernova remnant where, against all expectations, a lone surviving distant planet was found. An intelligent race in that solar system, foreseeing the coming cataclysm, had created a vast archive of their civilization for future visitors to find there. The narrator, a Jesuit priest, has a crisis of faith when his calculations reveal that the supernova that destroyed this civilization was also seen on Earth as the Star of Bethlehem. Pluto is about 40 times as far from the Sun as the Earth and its temperature is about 42 K. It would warm up under supernova conditions by a factor of 316 to a balmy 13,000 K, only 2.5 times as hot as the surface of the Sun. Since radiation is inversely proportional to distance squared, and temperature is proportional to the fourth root of radiation, it follows that temperature is inversely proportional to the square root of distance. Thus, to reach a temperature of 2000 K, where some materials at least might remain solid, a planet would have to be about 45 times as far from the sun as Pluto. It is very unlikely that any star would have surviving planets after a supernova explosion. Several cases of planets orbiting pulsars (supernova remnants) have been discovered (Stephens, 1996), but these are believed to be a second generation of planets that accreted from debris after the explosion. We can also take solace from the fact that stars likely to go supernova have lifetimes measured only in millions of years and are unlikely to have planets with intelligent

NO REFUGE

What if you were on the night side of the Earth when it happened? Larry Niven's (1971) short story The Inconstant Moon (later made into a script for the TV series The Outer Limits) deals with characters who realize the dazzlingly bright moon means a catastrophe on the day side of the Earth. In Niven's story, the catastrophe turns out to be a colossal solar flare that abates before sunrise, so that North America survives. The story is somewhat **THE HEAVINESS OF LIGHT** unrealistic in that only a few people realize what is happening, whereas the sudden cessation of all transatlantic communication, not to mention television broadcasts capturing the event before going dead, would probably result in very quick general awareness of the

catastrophe.

In Årthur C. Clarke's story Rescue Party (Clarke, 1959), extraterrestrial visitors come to Earth hoping to save at least a few humans before the sun explodes, only to have a landing party become stranded themselves. Their ship takes shelter in the Earth's shadow, using the Moon as a warning beacon and trusting in the ship's ability to surpass light speed before exiting the Earth's shadow cone. The last view the rescued aliens have of the Earth is its sudden illumination by the Moon, "shining with the brilliance of a second sun." The aliens later discover that humans had already fled the earth. To be strictly accurate, neither story uses the term supernova, although the Clarke story pretty clearly implies one. What would the full Moon look like when the Sun goes supernova? The Sun would brighten by 25 magnitudes (from +5 to -20 absolute magnitude, or -27 to -52 apparent magnitude). So would the Moon, which shines by reflected sunlight. The full Moon would brighten from magnitude -12 to -37, 10 magnitudes brighter than the present Sun, or 10,000 times brighter. The radiation flux would raise the temperature by the fourth root of 10,000, or 10 times, to 2700 K. That is about as hot as the surface of a type M star or the filament of an incandescent light bulb, or roughly like being at ground zero at Hiroshima (Glasstone and Dolan, 1977). One might imagine a few people surviving in suitable shelter (at least briefly). Bank vaults and missile silos are among the few shelters that might work for a while. The night side of the Earth would be only marginally less lethal than the day side. And sooner or later, the Sun will rise.

Maybe it's new moon when the disaster happens. Would that buy you a little time? The planet Venus is magnitude -4 at its brightest when it is closest to Earth. It would brighten to magnitude -29, or about six times as bright as the present Sun. This would be enough to raise temperatures to about 430 K (about as hot as a kitchen oven), but other catastrophes would intervene before Venus heated the earth enough to do significant damage. Even if there are no planets visible, there is still fine interplanetary dust. Sunlight reflected interplanetary dust, the so-called zodiacal light, is equivalent on the average to a faint naked eye star per degree of sky (Hawkins, 1965), or roughly the light of Venus spread out over the whole sky. A ten billion fold increase in sunlight would cause even the faint reflection from interplanetary dust to light the earth brighter than daylight. Nobody on earth would be unaware of what

was going on.

Sunlight refracted and scattered by the atmosphere reaches well into the night hemisphere of earth, and under supernova conditions this scattered light would increase by a factor of ten billion as well. A radiation flux 200 times that of the present Sun would heat the surface to over 1000 K, and that would happen if the pre-supernova sky brightness were 2 x 10-8 that of the Sun, or about the equivalent of a magnitude 3 star per degree of sky. This brightness corresponds to very deep twilight, so that lethal conditions would extend far onto

the "night" side of the earth.

The solar flux on earth is 1370 watts/m², and since the momentum of light is given by momentum = E/c, the momentum of the incoming light per second per square meter is 4.6 x 10⁻⁶ kg-m/sec. (One appealing feature of this formula is that we do not need to worry about the frequency distribution of the supernova radiation, only its total energy.) The units of momentum divided by time and area are the same as those of pressure; thus the pressure exerted by the light is about 4.6 x 10-6 pascals. If the solar radiation flux increases by a factor of ten billion. the pressure exerted by sunlight would increase to 46,000 pascals or about half an atmosphere. Thus the pressure of light would be quite effective in its own right but its effects would probably be dwarfed by the thermal expansion of the atmosphere. If temperature increases by a factor of 316, we could expect the heated atmosphere to reach on the order of 100 times or more its present pressure, even allowing for vertical expansion and stripping of the upper atmosphere. We could expect the expanding atmosphere to propel a shock wave far into the night side of the planet and of course the air behind it would be at temperatures of thousands of degrees.

ABLATION OF THE EARTH

How long would the Earth survive? The physical complexities of this problem are such that only order of magnitude estimates are worth making. Exact calculations would require us to account for high pressure phases within the earth, the behavior of the mantle and core, and the physical mechanisms of heat transport and ablation. But order of magnitude calculations are revealing enough to suggest the fate of the earth.

The heat of formation of olivine and enstatite from the elements, and thus the energy it takes to break them back down to their constituent atoms, is on the order of 10⁷ joules per kilogram (Navrotsky, 1995). At 85,000 K, we will not worry about the likelihood of molecules remaining. Under supernova conditions, our present solar flux of 1370 watts/ m^2 becomes 1.4 x 10^{13} watts/ m^2 . Assuming a density of 3000 kg/m³, it would take about 3 x 10¹⁰ joules to vaporize a cubic meter of rock, so that the energy flux would be sufficient to boil away the surface at hundreds of meters per second. The process would probably be somewhat less efficient in practice because of shielding by already ablated material, among other

The heat of formation of olivine and enstatite from the elements implies it would take on the order of 1032 joules to vaporize the Earth. By the time solar energy reaches the Earth, it is spread over a sphere 150 million kilometers in radius, and we intercept only the Earth's cross sectional share of that amount, or about 4.5 x 10⁻¹⁰ of the total. Given the present energy output of the Sun, the Earth intercepts 1.8 x 10¹⁷ joules per second. It would take several million years at this rate to intercept enough energy to vaporize the Earth, and of course the energy reradiates almost as fast as it arrives. Under our hypothetical supernova, the Earth would intercept 10 billion times as much energy, or 1.8 x 10²⁷ joules per second (four times the present total energy output of the Sun, all of it impacting the Earth). It would take on the order of 100,000 seconds, or about a day, to receive enough energy to vaporize the Earth. It would actually

Dutch - Supernova 29 take longer because much of the incident energy would quantitative reasoning. The most complex math in this be reflected or re-radiated, and it would also take time to paper is the Maxwell velocity distribution of particle strip off the outer layers of the Earth and reach the deep

interior, but probably no more than days.

What happens once the rocks vaporize? The most probable velocity of a molecule or atom in a gas is given by v = O(2kT/m) where k is Boltzmann's constant, 1.38 x 10-23 J/K, T is temperature and m is the mass of the atom or molecule. For a silicon atom of mass 28 (.028 kg/mole) at 85,000 K, v = 7100 m/sec. This, a bit surprisingly, is less than escape velocity (11,000 m/sec), but not very much less. The velocity of atoms in a gas obeys the Maxwell velocity distribution (Lodders and Fegley, p. 19), and many atoms would be moving faster and would escape easily. At present, the proportion of atmospheric molecules that exceed escape velocity is vanishingly small, on the order of 10-89 for nitrogen even at the 1000 K of the thermosphere. Under our hypothetical supernova conditions, effectively all hydrogen atoms, nearly half of nitrogen and oxygen atoms, 18 per cent of silicon and 2 per cent of iron atoms would exceed escape velocity. These fractions are so large that the earth's gravity would have at best a minor effect on delaying complete ablation. As the Earth boils off mass, its escape velocity decreases, making escape of the remaining atoms easier. A similar calculation for hydrogen on Jupiter shows that about one per cent of hydrogen atoms on Jupiter would exceed Jupiter's escape velocity of 60,000 m/sec, so that even Jupiter would undergo fairly rapid ablation.

The gravitational self energy of the Earth, or the energy it would take to disassemble all the mass of the Earth, is (3/5)Gm²/r, where G is the gravitational constant, m is the mass of the earth and r its radius. Treating the earth as uniform, its self-energy is 2.26 x 10³² joules, about the same order of magnitude as the energy required to vaporize the Earth. It would take about 36 hours to receive this much energy from the supernova Sun. Also, the supernova Sun would blast off a significant fraction of its mass at relativistic velocities. When it reaches Earth, it would be pretty effective at helping to strip off mass. The Earth wouldn't vanish instantly in a supernova explosion, but its survival time would be measured in days at best. If the Sun blasts away half of its mass, or 1030 kg, the earth would intercept 4.5 x 10⁻¹⁰ of the ejected mass, or 4.5 x 10²⁰ kg. This amounts to 1/13,000 the mass of the earth, but it would be moving at high speed. If it were moving at 10 per cent of the speed of light, its total kinetic energy would be 4 x 10³⁵ joules, or about 75 times the orbital kinetic energy of the earth and 4500 times the energy required to vaporize the earth. Its momentum would be about 3/4 the orbital momentum of the earth. As the comic strip character Dogbert put it in a different context, it would be "like sandblasting a soup cracker."

PEDAGOGICAL APPLICATIONS

I first conceived of the scaling approach to picturing the Navrotsky, A., 1995, Thermodynamic Properties of effects of a supernova several years ago and use it mostly in an astronomy course designed for non-science majors where math skills are minimal. I give them a very brief synopsis of the math to show that the numbers are justified. Although students generally find supernovae dramatic and interesting, they react visibly to this analogy in a way that a description of supernovae as remote stellar events does not inspire.

Most of the analogies given in this paper involve no more than algebra and would be suitable for any astronomy or planetary science course that requires velocity. The distribution function is given by

$$F(v) = 4\pi N(m/2\pi kT)^{3/2}v^2 \exp(-mv^2/2kT)$$

where N is the number of particles, m is the particle mass, T is temperature, v is velocity and k is Boltzmann's constant. For purposes of visualizing velocity distribution, we can let N be any convenient value like Avogadro's Number. To determine the total fraction of atoms above or below a given velocity we need to integrate the function from $\tilde{v} = 0$ to the desired velocity; this can easily be done numerically using a spreadsheet. This would be an exercise appropriate for an upper-division undergraduate class in astronomy or planetary science.

The area of the visible sky is easy to derive even if the radius is indeterminate. The area of a sphere is 4pr², and its circumference is given by C = $2\pi r$. Thus the area of a sphere in terms of its circumference is $C2/\pi$. The circumference of the sky is 360 degrees, therefore its total area is 41,253 square degrees and the visible hemisphere

has an area of 20,626 square degrees.

REFERENCES

Ahrens, T. J., ed, 1995, Global Earth Physics: A Handbook of Physical Constants, AGU Reference Shelf 1, p.159-189 Washington, D.C., American Geophysical Union, 376 p.

Arnett, W. D., Bahcall, J. N., Kirschner, R. P., and Woosley, 1989, Supernova 1987A, Annual Review of Astronomy and Astrophysics, v. 27, p. 629-700.

Clarke, A. C., 1959, The Star, in From the Oceans, From the Stars, New York, Harcourt, Brace and World, p.

Clarke, A. C., 1959, Rescue Party, in Across the Sea of Stars, New York, Harcourt, Brace and World, p. 149-174.

EFNS (Educational Foundation for Nuclear Science), 2002, NRDC Nuclear Notebook: Global nuclear stockpiles, 1945-2002, Bulletin of the Atomic Scientists November/December 2002, v. 58, p. 103-104.

Glasstone, S., and Dolan, P. J., 1977, The effects of nuclear weapons, U.S. Government Printing Office, 653 p.

Hawkins, G. S., ed., 1965, Meteor Orbits and Dust, NASA Special Publication SP-135, 412 p.

Lodders, K., and Fegley, B., 1998, The Planetary Scientist's Companion, Oxford University Press, New York, 371 p.

Marschall, Laurence A., 1988, The supernova story, Plenum Press, New York, 296 p.

Murdin, Paul. 1990. End in fire: the supernova in the Large Magellanic Cloud, New York, Cambridge University Press, 251 p.

Minerals, in Ahrens, T. J., ed., AGU Reference Shelf 2, Global Earth Physics: A Handbook of Physical Constants p. 18-28, Washington, D.C., American Geophysical Union.

Niven, L., 1971, The Inconstant Moon, in All the Myriad Ways, New York, Ballantine, p. 124-153.

Stephens, S., 1996, Second Chance Planets, Astronomy, v. 24, p. 50-55.

Wheeler, J. C., 2000, Cosmic catastrophes: supernovae, gamma-ray bursts, and adventures in hyperspace, New York, Cambridge University Press, 288 p.