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A History of Gamma Ray Bursts and Other Astronomical Conundrums

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Abstract. The 24 years between the announcement of “gamma-ray bursts of cosmic origin” (1973) and the unambiguously cosmological 970228 seemed very long to the generation that lived through them. For a good many astronomical phenomena, however, the interval between the recognition of a puzzle and convergence of the community on a solution was even longer. Examples include periodic variable stars and coronal lines from the sun. In other cases, the right idea has appeared very soon after discovery, pulsars and quasars, for instance. Sometimes, on the other hand, the theorists are out in front with an explanation in advance of the discovery. This is called a prediction, and some have come very far in advance (heliocentric parallax surely holds the record), others only a few years (superluminal motion in quasars, for example). The talk and this paper explore a few examples of each class as a framework for the much-told GRB story.

Keywords: Gamma Ray Bursts, Pulsating Variable Stars, Astrophysics.

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INTRODUCTION

Science can be described as the on-going comparison between data and ideas, with data sometimes laboriously sought, sometimes dumped on our plates, and ideas sometimes put forward *sui generis*, sometimes dragged up to deal with unexpected data, and, if all goes well, sometimes discarded when conflicts persist. I have pontificated on the history of GRBs on a number of previous occasions (Trimble 1992a, 1992b, 1993, 1994a, 1994b, 2004, 2005) and so here focus on how astrophysical consensus has been established in various cases.

There are two typical patterns, with variations. Sometimes the data lead, and an observation is perceived as puzzling, perhaps immediately, as in, obviously, the case of GRBs, perhaps not until many years later (1845 to 1896 for spiral arms). Multiple explanations are then put forward, and convergence occurs, again rapidly (pulsars) or very slowly (nature of dark matter). The convergence may hold down to the present, in which case we say we have a theory of the phenomenon (stellar structure and evolution may be the cleanest). Or it may be disrupted by additional data, to be followed by another consensus model (the GRB case). Naturally there are phenomena for which we are currently somewhere in the middle of these processes.

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Alternatively, ideas may lead and a prediction be made. The phenomenon is then sought, sometimes immediately and repeatedly (heliocentric parallax and a neutron star in the remnant of SN1987A), sometimes not until a good deal later (gravitational radiation), and sometimes not at all, so that discovery surprises nearly everyone (the CMB).

The search can be long (parallax, from the Greeks to Henderson, Bessel, and Struve surely holds the record) or short (21 cm radiation). The first positive report may be confirmed (21 cm radiation within weeks; parallax in a couple of years) or falsified (the planet that does not orbit pulsar psr 1829-10). And if the search is long and unsuccessful, predictions will be forced downward (solar neutrino flux, fluctuations in the CMB) until, eventually, the twain meet and we have again consensus. Sometimes this sort of agreement can also fall apart (many observers reported Vulcan, the dragger on the orbit of Mercury, and, of course, cyclotron features in GRB spectra). But theories that predict phenomena before they are seen, like deflection of light by the sun, are generally held in high repute by the scientific community. Once again, we can find ourselves today at any stage of this process. Predictions for which direct evidence is still being sought include ultra-high-energy neutrinos (from GRBs or anything else), a pulsar with a black hole companion, proton decay, that neutron star (or even black hole) left from SN 1987A, Hawking radiation, gravitational radiation, and dark matter particles. What we all, of course, wish we could recognize are the cases where the current convergence is around the wrong idea, so that we could be in the vanguard of the revolution.

The following sections are brief “case studies” illustrating these patterns. GRBs come at the end.

STELLAR PULSATION

The novae stellae of Tycho and Kepler were followed by quite a number of reports of other new stars, including “a nova in the whale” spotted by Fabricius in 1596 and Howards in 1638. Helvelius recognized that the two were the same star (1662), and Boulliau showed that the variation was periodic (1667). He also put forward the first explanation, rotation of a star with much darker spots than those on the sun. This was the only idea in the bank for more than a century.

Edward Pigott and John Goodricke recognized the periodicity of Algol (reported as variable by Montanari in 1669) in 1782, when Goodricke was still a teenager (he was dead at 22), and proposed that they were seeing an eclipse by a large, dark companion. They applied the same idea to δ Cephei, whose periodicity was Goodricke’s discovery, in 1784. Eclipsing binaries were then the consensus model for all stellar variability for more than a century. Curiously, Goodricke and Pigott themselves realized that the eclipse hypothesis made definite predictions – precise periodicity and symmetric light curves – not actually fulfilled by δ Cephei and η Aquilae, and seemingly not in their data by Algol, and abandoned the eclipse model.

More serious, eventually astrophysics developed to the point where one could estimate sizes of stars from their colors and luminosities, and it became clear that the

orbital diameter of an eclipsing δ Cephei would be smaller than the sum of the radii. But theoretical understanding of stars had also advanced enough that, first, Plummer (1912), then Shapley (1914), and definitively Eddington (1926) recognized that a pulsating star, with simultaneous changes in radius and temperature could reproduce the observed light curves. Eddington identified the correct driving mechanism as well, a step in the ionization of an abundant element near the surface of the star. Hydrogen, we now know, but for Eddington H was 7% contaminant, not the solution.

This particular puzzle took more than 250 years for sorting out and arguably holds the long duration prize, although Kelvin could plausibly have demonstrated that pulsation yields at least the right time scales. Notice that orbital motion at contact and pulsation differ by only a factor of two or so, since both are manifestations of time $\propto (G\rho)^{-\frac{1}{2}}$.

THE SOURCE OF SOLAR AND STELLAR ENERGY, GIANTS, AND THE SOLAR NEUTRINO PROBLEM

That the heat and light of the sun would require maintenance became clear only with the 19th century establishment of universal conservation of energy. John Herschel suggested friction (presumably with some transparent substance) or electrical discharges. The story of how Julius Mayer and John Waterston recognized the problem in 1841 and 1843 respectively, proposed infall or contraction as the solution, and lived to see the credit go to Kelvin and Helmholtz has been told by Hufbauer (1991), and I will note here only the sad sideline that Mayer's paper was refused by the proceedings of the Paris Academy and Waterston's by the Royal Society. The 30,000,000 or so years the sun could live on contraction is invariably called the Kelvin-Helmholtz time scale. That it was not enough was gradually forced upon the physics and astronomy communities by uniformitarian geologists and Darwinian biologists. The laboratory discovery of radioactive decay led to the idea of subatomic processes as the dominant source of energy.

Key intermediate steps were (a) $E=mc^2$, (b) laboratory measurements of atomic masses in Cambridge (particularly hydrogen and helium) by Francis Aston starting in 1922, (c) the gradual recognition that stars contain very large amounts of hydrogen and helium, pioneered by the 1925 thesis of Cecilia Payne, and (d) the concept of barrier penetration, found in embryo form in Atkinson and Houtermans (1931) who suggested catalyzed cyclic reactions (details necessarily wrong because the neutron had not yet been discovered), but normally credited to Gamow and Condon and Gurney. And the problem was generally regarded as solved from the publication of Bethe (1939) onward. Notice that both special relativity and elementary quantum mechanics were needed. And we touch current events as well. Very many of us knew Bethe, and I was offered a job at Indiana by Atkinson in 1968.

Eddington (1926) had supposed that observed giants were actually contracting stars in the process of formation from diffuse material. A few of them of course are. The rest fall out of calculations of stellar evolution with little or no mixing. The role of

composition (mean molecular weight) discontinuity was noted by Öpik (1938) and Hoyle and Lyttleton (1939). Schwarzschild's work (summarized in Schwarzschild 1958) made clear that red giants would indeed happen and that purely verbal descriptions of just why would never quite satisfy (which is why they continue to appear in the literature even now).

And then, after we had all been certain things were under control, came the discordance of prediction and observation of solar neutrino flux. See Bahcall (1989) for many details and references, but it is worth nothing here, first, that the range of explanations presented between about 1969 and 1989 surely rivaled the GRB inventory of hypotheses, ranging over chemistry, nuclear physics, astrophysics, and weak interactions and, second, that the right idea, neutrino oscillations, was in the inventory from the beginning, thanks to the inspired thoughts of Bruno Pontecorvo. I am not quite sure when this became the dominant idea (I switched when Bethe became firm about the issue, about 1994), but it became inescapable with the results from Super Kamiokanda and SNO, seeing the oscillation products first for cosmic-ray-induced neutrinos and then for the solar ones.

Durations? Well 106 years for the energy source if you count Herschel to Bethe; only a decade or two for red giants; and zero to 25 years for the solar neutrino puzzle, depending on when you personally came over to the oscillating side. Truthfully, a few living scientists still do not quite subscribe to a standard sun that began 4.56 Gyr ago as a homogeneous sphere of mostly hydrogen and helium, but none is young.

Well, while we are close to the sun, let's look at the coronal emission lines, first reported by Charles A. Young in 1869 and quite widely then attributed to an element to be called coronium by analogy with helium, responsible for some solar photospheric features, and nebulium, the source of emission lines from diffuse hot gas. Hufbauer (1991, p. 112) also tells the story. The culture heroes are Walter Grotrian and Bengt Edlen, who engaged in some competition for first formal publication of the line identification with highly ionized iron and other elements in 1939. Duration a mere 70 years. Much new physics, from Bohr to Schroedinger, was required, and if you are absolutely sure you fully understand why stellar coronae are this much hotter than their photospheres (something times 10^6 , vs. something times 10^3 K), and you can persuade most of us to agree with you, the duration of that puzzle can be truncated at 67 yr.

THE ADVANCE OF THE PERIHELION OF MERCURY AND SOME ALSO-RANS

Since the discovery was announced in 1859 (by U.J.J. Leverrier, see Hoskin 1999) and Einstein's explanation in 1915, we are down to a mere 56 year duration. But it was marked by another of those convergences around a wrong idea – the planet Vulcan, seen in transit some 20 times between 1859 and 1876, but apparently never again, though Leverrier had predicted additional transits in March 1877 and October 1882. About 1900, Simon Newcomb (who otherwise doesn't get much good publicity these days) was among the advocates of a deviation from pure $1/r^2$ gravity as the explanation. And, curiously, there was a very late attempt to break up the consensus,

when Robert Dicke attempted to support a general relativistic variant called the scalar-tensor theory with measurements of the diameter of the sun implying an appreciable oblateness and quadrupole moment which would, of course, give the effective gravity a $1/r^3$ component. In retrospect, Dicke and Goldenberg (1967) probably observed facular brightening of the solar equator, but if they had been right, the perihelion puzzle would have extended another 50 years. And the “what was needed” box would have held two new theories of gravity beyond Newton.

A few of my favorite also-rans include (a) stability of spiral arms in the presence of differential rotation, solved perhaps by C.C. Lin and F.H. Shu in 1964 (solitons) or perhaps not yet entirely, (b) the acceleration of cosmic rays, solved perhaps by E. Fermi in 1949 (38 years after the discovery that they are extraterrestrial), or perhaps not yet entirely, (c) the cause of nova explosions (discovery, arguably T Pyx in 1919, and attribution soon after by Milne to collapse of a normal star to a white dwarf). Eddington, however, recognized that novae must recur on statistical grounds, and the establishment of universal binarity and hydrogen fusion explosions on the surface of an accreting white dwarf stretched out from about 1946 to 1963.

A FEW PREDICTIONS AND THEIR FATE

Two of my favorites are polarization items, one with very rapid discovery of the predicted effect, one much more complicated. The quick case was optical polarization in the Crab Nebula, seen by Dombrowski (1953, who sadly spent most of the rest of his career looking unsuccessfully for polarization of other, thermal, nebulae), very soon after V.L. Ginzburg and I.S. Sklovsky said (separately!) it should be there. For details of this and of the prediction of circular polarization from the Crab, whose proposers honorably abandoned their hypothesis when it wasn't detected (Rees and Gunn 1974), see Trimble (2003). The Crab is also host to several other long-unconsensused phenomena and unfulfilled predictions.

The more convoluted case begins with a prediction from Chandrasekhar (1946) that light coming to us from hot stars should be somewhat polarized by electron scattering in the stellar atmospheres. John Hall and William Hiltner, then both also at Yerkes, set out to look for the effect, though by the time they published, there were two separate papers, Hall (1949) and Hiltner (1949). They found polarization all right, but so systematically aligned with the galactic plane that anything happening in the stars themselves seemed most unlikely.

Aha! A “pattern I” of unexplained observation. But Davis and Greenstein (1951) and Gold (1952) soon came forward with (different) hypotheses. Davis and Greenstein invoked scattering by interstellar dust grains alighted by a galactic magnetic field, not yet then known to exist, while Gold proposed scattering by spinning grains whose alignment was due to large scale gas flows rather than magnetism. Incidentally, current understanding requires both magnetic field and spin.

Chandrasekhar's effect was finally reported by Kemp et al. (1982). That one took 36 years. James C. Kemp, a free spirited Oregonian much given to the wearing of Hawaiian shirts, belongs somewhere around here in another context, for the discovery of polarization of white dwarf light (Kemp et al. 1970), the first clear evidence for strong magnetic fields in these stellar cinders. It would be interesting to chase down

the predictions and discoveries of magnetic fields in all the contexts where they are known or suspected and to sort out the stories into the various possible patterns. The fields one would have to worry about include that of earth (1600, Gilbert), the sun (1908, George Ellery Hale), the interstellar medium (briefly here, but also Fermi acceleration of cosmic rays), Ap stars (H.D. Babcock), white dwarfs, neutron stars and supernova remnants, intracluster and intergalactic media, and, of course, gamma ray bursts. I should think that the 80% polarization of one event, mentioned briefly at the present conference, would have counted as a detection if the polarization were a little more persuasive

The GRB field also has examples of both prompt and afterglow detections of predicted phenomena and of explanations that came along too early to have much influence. Meszaros and Rees (1997) forecast an optical afterglow very shortly before it was found. Rhoads and Paczynski (1993) forecast a radio one a little too early for it to have been in mental forefronts in 1997. They noted later that they "should have" realized that the radio tail would be part of more extensive emission, including visible light and X-rays.

GAMMA RAY BURSTS, PART I: WE HAVE TURNED EVERY ONE TO HIS OWN WAY

The discovery paper (Klebesadel et al. 1973) was squeezed into the length of an Astrophysical Journal Letter, and more of the process is described in Strong et al. (1975, the observational summary talk on GRBs at the Seventh Texas Symposium on Relativistic Astrophysics). The Los Alamos group knew about the Colgate (1968) prediction that supernova shock outbreak should radiate a burst of gamma rays and deliberately looked for signals in the direction of known supernovae during the period before 1973 without seeing any. They also knew that solar flares could be sources of very hard photons (Cline, Holt, and Hones 1968, whose third author was at Los Alamos, and whose first two were at the present meeting), looked for those, and saw them. They also decided to check for other (conceivably astronomical) events that could produce simultaneous triggers in both Vela 5 and Vela 6, without being supernovae, solar flares, or the bomb tests that were the original goal of that satellite series.

Thus were found the GRBs, and I would claim the discovery was not precisely serendipitous in the original sense of the word. The Russians had also worried about secret atmospheric or surface bomb tests, though at the time Mazets et al. (1974) reported that they had seen at least one of the Vela GRBs, I did not quite believe that the use of Cosmos 461 implied the existence of 460 previous launches. But the first was 16 March 1962, and the end of 1967 took the series to Cosmos 198, the majority of the payloads by then being "unannounced", not that the public description of, say, Vela 7 ("advanced nuclear detection satellite") was enormously more informative (TRW Space Log, Vol. 7, No. 4).

Truly spectacular were the thousand (well 118, Nemiroff 1994) flowers of theory that promptly blossomed. Among the more notable are the Colgate (1968) and Hawking (1974) predictions (the latter still in that category because the author does not give the impression of having heard of the observations); Jelley's (1974) proposal

of a Leblanc-Wilson type collapse of a rapidly rotating, magnetized star, not so very different from the current understanding of long duration bursts; and Harris (1990) who looked for lines of GRBs across the sky that might be exhaust trails from interstellar space craft operating on electron-positron annihilation. This was in the era of general acceptance of spectral features, including a redshifted 511 keV line, that we face in the next section. And Fritz Zwicky's last published paper (Zwicky 1974) credited free explosions of chunks of escaping neutron star material, which he called Goblins.

Occasional models invoked entities that very probably exist in the universe but may not have much to do with gamma ray bursts, for instance Paczynski (1987 on gravitational lensing) and Paczynski (1988 on superconducting superstrings).

Less unconventional events in solar system, Milky Way, and cosmos also appeared. By the time Ruderman (1975) provided the theory review at the 7th Texas Symposium, he claimed that only anti-matter comets hitting white holes had gone unclaimed, though he himself was betting on "black hole ridden by accretion" to win and "glitch" to place. Very curiously, at that same meeting, Colgate disowned his prediction, saying that he thought that supernovae would indeed make hard photon bursts, they just hadn't been seen yet. Today we would probably say that he was right the first time. Ruderman also claimed that the only theorist who did not have a GRB model was J.P. Ostriker. Ostriker (personal communication 2003) reports that he still hasn't published one, but has given some thought to electromagnetic processes. The remark of Brecher and Morrison (1974) that the energy must be tightly beamed was also prescient, though they had in mind stellar flares as the energy source.

GAMMA RAY BURSTS PART II: ALL WE LIKE SHEEP HAVE GONE ASTRAY

A young participant suggested after my talk that so few astrophysicists now either read Isaiah or participate in Christmas Messiah sing-a-longs that the origin of this section title and the previous one might need their origins explained. There you have your pick of two.

Less than a decade after Klebesadel et al. (1973) saw light of print, the community had reached remarkably broad consensus on a model where GRBs were events on the surface of old, nearby, but still highly magnetized neutron stars. Lamb (1984, from the 1982 Texas Symposium) provides a good taste of the flavor of confidence of this conclusion. How did we manage to do this?

There were, I think, a handful of key events, beginning with the discovery of X-ray bursters (which is why the name is not available for gamma-poor GRBs!) in 1976-77 by Grindlay, Lewin, and their collaborators, followed quickly by a correct interpretation in terms of explosive helium burning on accreting neutron stars by Paul Joss. Woosley et al.'s (1976) idea of carbon detonation had originally been intended as a GRB model and so has the status of a prediction for recently-identified subclass of XRB where it is carbon that flashes! The X-ray bursters provided an honest, early hint of their brightnesses and nature by concentrating themselves in the general direction of the galactic center, while the GRBs were isotropic then and always.

In the same time frame came the discovery (from a balloon flight by the Truemper group in 1976) of cyclotron resonance features in the X-ray spectrum of Her X-1. Such have been found since in many XRBs and point us correctly toward strong magnetic fields. But similar features began popping up in GRBs: a redshifted positron annihilation line; 847 keV iron redshifted by the same amount; 20-70 keV cyclotron resonances, sometimes more than one per burst and in seemingly the right frequency ratio. Lamb (1984) provides extensive references, but let Mazets and Golonetskii (1981, a Venera result) stand for all the rest, including reports from SMM, HEAO-1, and especially Ginga. I was not in any way immune to this virus and in a 1990 review describe GRBs as "mergers of binary neutron stars with strong magnetic fields at cosmological distances."

Third, for a while it seemed that the events must be recurrent, because there were occasional optical flashes found on old photographic plates in the error boxes of recent GRBs, a 1978 burst on a 1928 Harvard plate, for instance. The implication was that the object involved must survive and be able to try again in a century or less. Next came the "no host" problem, with searches for host galaxies in GRB error boxes coming up empty right up to the time of 970228, when we all had to face the fact that at least some hosts were very distant, faint, blue galaxies.

Discovery that some neutron stars are very high velocity objects (the current record is something like 1000 km/sec) and so could populate an extended galactic halo contributed its mite of confusion as well, at the onset of the CGRO era. The reason this mattered was that the plots of numbers of GRBs vs peak flux or fluence (total energy received) finally began to turn over from the slope of 3/2 associated with homogeneous, isotropic populations. Such a turn-over had to occur at some flux for neutron stars in the galactic disk, and indeed there had been early reports, generally then attributed to assorted instrumental problems. I think the first that should have been credited was White et al. (1983) but nobody much asked me at that time.

Now, what does this have to do with runaway stars? Well, if we see the end of a distribution (the turn-over) but are at the center of it (the isotropy on the sky), only three possible sites remain: some part of the solar system much larger than 1 AU, some part of the Milky Way much larger than 10 kpc, or some part of the whole universe, larger than the distance at which redshift effects became important. Fishman (1995) concisely describes the situation at the point when CGRO had forced the simultaneous center/edge phenomena on us but before the first optical identifications, but the loudest voice crying in the wilderness that center + edge must mean cosmological distances was that of Paczynski (1991).

THE MISSED OPPORTUNITY AND THE BENEFICIARIES

Proposals for instruments to be carried on the Gamma Ray Observatory (later Compton Gamma Ray Observatory) exceeded the number of slots available, and so there was, of course, a peer review panel. It was my second (Space Telescope was first in 1977). Among the proposals were two (one from Walter Lewin and his colleagues, one from Paul Gorenstein and his) for X-ray imagers in the 20-50 keV range. These would have provided arc-minute positions from the long-wavelength tail of the brighter GRB events themselves. Neither was selected, primarily on the

grounds that these were clearly X-ray instruments, and there were already several X-ray satellites with more in the pipe line. Bernie Burke's recollection (personal communication 2005) of how this view was expressed is harsher than mine. Since then I have merely said that the line between X-ray and gamma ray astronomy has nothing to do with photon energy or the emission process. It is merely that X-ray astronomy is done by X-ray astronomers and gamma-ray astronomy is done by gamma ray astronomers, and even now the twain don't seem to meet much oftener than they have to. I guess we should just all be glad the BATSE made the cut and that Fishman (these proceedings) was able to hold out for eight detectors on the eight corners!

If a CGRO X-ray imaging detector had flown, a good position leading to an optical counterpart might easily have been found by the fall of 1991 (BATSE started finding bursts in April.) Instead it was February 1997, and the requisitely accurate X-ray position came from the Beppo SAX, mostly Italian, satellite, launched in April 1996.

It has proven remarkably easy to get used to the extragalactic consensus, though as late as the 1995 diamond anniversary restaging of the Curtis-Shapley debate (Nemiroff 1995) a fairly sophisticated audience, asked to vote, were more or less equally divided between a Milky Way corona and the universe. It is also true that the fraction who voted "uncertain, or decline to state" was a good deal larger after the debate than before. And it remains true down to the present that GRBs seem to be the only class of astronomical source in which cosmological effects of redshift can be seen clearly over and above astrophysical ones of the evolution.

CONSENSUS AND AN EXERCISE FOR THE STUDENT

It is, I think, fair to say that the community now agrees that GRBs or at least the vast majority, are very high energy events that we can see from essentially the entire observable universe, though some details remain to be worked out, to put it tactfully. These include both the precise engines for the short duration events and many aspects of the processes by which the raw energy is transformed into the photons we see. Remember, however, that we felt the same way in 1985, except that the events were relatively low energy, repetitive and confined to some portion of the Milky Way, at least as far as the ones we could see.

The following is a partial list of astronomical phenomena that I think have interesting histories within the patterns of data leading vs ideas leading and fast vs slow progress to the next step. Some have been mentioned above, many not. Feel free both to decide which pattern you think each illustrates and to let me know of phenomena that should be added to the list. Blazhko effect. Second parameter in globular clusters. Oosterhoff types. Pulsars with BH companions. Ultra-high-energy neutrinos. Cosmological neutrinos. Proton decay. Extra-solar-system planets. Primary cosmic ray anti-protons. X-ray fluorescence from moon. Chandler wobble. Rings of Saturn. Lambda Boo stars. Extra-SS gamma rays. Radar echoes from cosmic ray showers. X-rays from cool, single magnetic white dwarfs. Cosmic rays above the GKZ limit. Intermediate mass black holes. Magnetic fields in white dwarfs. 3K microwave background. Solar and stellar flares.

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