Title
CREATORS RECORDS - THE PREHISTORY OF SINGLE AND BINARY NEUTRON-STARS

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CREATOR'S RECORDS: THE PRE-HISTORY OF SINGLE AND BINARY NEUTRON STARS

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ABSTRACT

Single neutron stars were thought of more than 30 years before they were observed (and even then were not instantly recognized). Binary neutron stars, on the other hand, were observed before they had been though of as a separate, interesting class, and were also not immediately recognized for what they were. The traditional apportionments of credit for the various ideas are not fully supported by contemporaneous publications.

1. INTRODUCTION: DYSON'S LAW

Soon after the death of Richard Feynman, the American Physical Society and American Association for the Teaching of Physics honored his memory with a joint meeting session. Freeman Dyson spoke of their years together at Cornell, quoting letters he had written to his parents at the time and other documents. He began by saying that, in rereading these pieces of paper, he had been astonished both by how many things had happened that he had forgotten and by how many things he remembered that had never actually happened. Neutron star astronomy, undoubtedly in common with all other forms of human endeavor, shows examples of both phenomena. The sections following address single neutron stars, binary ones, and some special topics including accretion disks and globular cluster sources.

2. SINGLE NEUTRON STARS

Though Eddington was already sure in 1926 that stars must run on subatomic energy, the bandwagon was slow in gathering steam, and the literature of the 30's includes a mix of gravitational and nuclear processes. Milne (1931) attempted an early synthesis, toward the end of which he says, "It is possible that the passage of a configuration through the critical value $L = L_o$ may be discontinuous, as it certainly is for perfect-gas configurations of unlimited compressibility. If subsequent analysis confirms this, the passage of a configuration through $L = L_o$ would exhibit the phenomena of a nova, and we should have the suggestion that every star passes through a nova stage as it crosses from a configuration of ordinary density to one of great density, as its evolution of energy decays." This suggestion that novae are the transition from perfect-gas stars to degenerate white dwarf stars lingered in text books into the 60's.

Milne's idea was presumably still in the air when the words "neutron star" first appeared in print in the sentence, "With all reserve, we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons... [which] would represent the most stable configuration of matter as such." (Baade & Zwicky 1934). They go on to suggest a connection with cosmic rays and the Crab Nebula. The idea of the stability of neutron rich matter, in the context of nuclear transformations, is also present in Sterne (1933).

Meanwhile, Chadwick in Cambridge had discovered the neutron in 1932. The news clearly diffused rapidly. Four decades later, in an after dinner talk and conference proceedings, Leon Rosenfeld (1973) recalled being in Copenhagen at the time, where Bohr received a letter from Chadwick and discussed it with him and Lev Landau, who invented the concept of neutron stars on the spot. This tale has become part of the oral folklore we relate to our students (being precisely the sort of thing one can imagine Landau doing). Unfortunately, "At the time in question (February or March 1932) none of the three protagonists was in Copenhagen (Landau had moved to Kharkov). The conversation may have taken place during a meeting in the Soviet Union two years later." (Israel, 1987, making use of information unearthed by Gordon Baym). Baade and Zwicky apparently invented the concept of neutron stars as well as the name and the connection with supernovae.

They were to get precious little immediate glory out of it. Revising a monograph in 1937, Gamow writes, "For still higher densities electrons will probably be absorbed by the nuclei (an inverse β-decay process) and the mixture will tend to a state which can be described very roughly as a gas of neutrons." In the following calculations he cites only two papers (Landau 1932, which is shelved with JETP in many libraries, and Chandrasekhar 1931). Both are white dwarf and only white dwarf calculations (though Frenkel 1928 had considered the consequences of degenerate protons). Baade and Zwicky are not mentioned, and Gamow does not have catastrophic collapse in mind. Rather he says, "The question whether most stars at present actually possess such nuclei cannot, however, be answered definitely...but there seems to be no reason why they should not...As to the liberation of energy, one can easily see that pure gravitational energy liberated in the contraction to such immense densities will already be quite enough to secure the life of the star for a very long period of time."

Landau's (1938) much-cited neutron star paper is actually called "Origin of Stellar Energy," and says "...we see that the conception of a 'neutronic' state of matter gives an immediate answer to the question of the sources of stellar energy...Even for such a bright star as β Orionis, we find for the mass of the neutronic core only about 0.1$\odot$." Strangely, when Gamow and Teller (1938) come to say him nay, only the Landau proposal, not the Gamow one, is mentioned. They correctly conclude, "... that in the neighborhood of the core temperature will rise with r^{-1} and density with $r^{-3/2-n/2}$...[and] will reach the extremely high values more than 10^9 degrees and 10^9 g cm^{-3}. Under such conditions all kinds of nuclear reactions will proceed at a great rate and and will make the total energy production of the star many orders of magnitude greater than the observed radiation. Therefore the core model as well as any other model leading to such high temperatures seems to be ruled out. This had to be rediscovered 35 years later when the solar neutrino problem led to a suggestion (attributed to Hawking) that the sun might have a small central black hole, accretion on to which was the primary energy source. The exceedingly high temperature and density actually result in more neutrinos than the standard nuclear sun should radiate!

Serious neutron star models begin with Oppenheimer and Volkoff (1939). They say quite correctly "that in sufficiently massive stars after all the thermonuclear sources of energy, at least for the central material of the star, have been exhausted a condensed neutron core would be formed." But who gets the credit? "G. Gamow... L. Landau,...and others," the first two of whom, at least, said no such thing. Not Baade and Zwicky, who did, more or less.

Stellar astrophysicists in the immediate post-war years largely focussed on main sequence and red giant structure, making use of the detailed nuclear reaction chains identified by Bethe and others in 1939. Neutron stars (and black holes) reappeared, however, as part of the revival of relativistic astrophysics in the groups centered around John A. Wheeler (in Princeton from about 1957 onward) and Yakov B. Zeldovich (in Moscow a few years later). Seminal speculations were rife, and there can hardly be an astrophysicist old enough to remember the period who is not still kicking himself for not having published more of them and more agressively (Compare elderly Californians trading stories about how they could have bought the site of "One Wilshire Blvd" for $350 back in 1931.) Two of these speculations are particularly germane to our story. "If a star contracts in a spherically symmetrical way and if flux is conserved [and] if neutron star densities are reached the field intensity would increase by a factor of 10^{10}, and thus stellar fields of up to $10^{14} - 10^{16}$ G could be reached...one may well speculate that such a theory could have a direct bearing on the problem of the origin and acceleration of the relativistic electrons in the Crab Nebula" (Woltjer 1964). And Pacini (1967) mused, "The problem therefore arises of finding out whether the energy stored in the neutron star plays an important part in connextion with the activity observed in some supernova remnants such as the Crab Nebula. The vibrations of the neutron star, however, do not last long enough for our purpose...It seems more rewarding therefore to look for some mechanisms by which the neutron star can release either its magnetic or its rotational energy or both." There follows the standard expression for emission by a rotating magnetic dipole (for which most of us cite Gunn and Ostriker, though they in turn credited Landau and Lifshitz).

Even as he wrote, Hewish and his colleagues (1968) were stringing the wires and reeling out the punched paper tape and strip charts whose contents would soon be announced as, "Observations of a Rapidly Pulsating Radio Source [whose] radiation may be associated with oscillations of white dwarfs or neutron stars." White dwarfs were definitely ruled out by the Crab pulsar's 0.033 sec period and oscillations by the positive sign of the first-measured period change (also the Crab). The last fundamentally wrong paper on the subject may well have been Trimble (1969) on the "Frequency of Events Producing Pulsars."

3. BINARY NEUTRON STARS

Herbert Gursky has described on several occasions the events surrounding the discovery of what we now call Sco X-1 (Giacconi et Italia 1962), including the first attempt at optical identification: "So we got a star atlas and opened it up...and discovered there were a lot of stars in the sky; so we closed it again." Not surprising for a 10 X 10^{o} error box. Meanwhile, Hawakawa and Matsuoka (1964) considered the possibility that known classes of early type binaries might be detectable X-ray sources, "If the plasma stream ejected from one star hits the atmosphere of the other, a shock wave can be produced." Even their most optimistic stream velocity of 1000 km/sec achieved a luminosity of only 2 X 10^{34} erg/sec. The proposed mechanism is roughly that we now associate with X-rays from RS CVn stars and cataclysmic variables, though very few reach even this modest luminosity.

Successful optical identification of Sco X-1 (Sandage et al. 1966) followed closely upon an improvement of the X-ray position, the photometry and spectroscopy having been shared between Japanese and American observers in June-July 1966. The optical counterpart was summarized as having "certain of the properties of an old nova, even though its spectral characteristics cannot be identified with any one class of old nova." Bruno Rossi carried the news to Europe, to IAU Symposium 31 ("Radio Astronomy and the Galactic System") in Nordwijk, almost simultaneously with the 27 August submission of the identification paper.

At this point, relationships become both strained and numerous. The contemporary account of the discussion at Nordwijk (Burbidge 1967) mentions Rossi, Ginzburg, Shklovskii, Woltjer, himself and other (unnamed) participants. Strong connections with old novae were assumed. Discussion focussed on energy sources, especially gravitational energy, either "the gravitational energy of the binary system [or] we must derive the energy from the internal energy of one or the other of the stars...one might suppose that the highly evolved component of the binary system is a neutron star, and that the internal energy of this star is being slowly released in the form of high-velocity gas." (It is worth recalling that informed opinion by then recognized, largely on the basis of work by R.P. Kraft, that old novae were binaries with white dwarf components). Ginzburg is quoted as saying, "...the potential and kinetic energy of the double system is of the order of 10^{49} erg. This is an enormous amount, and we must find ways to use it for maintaining the X-ray emission. Tidal effects may produce streams of matter or stellar winds, and they may hit the surface of a star or produce a transient atmosphere." Notice first that the proposed energy reservoir will keep a bright XRB going only 3000 yr, and second that the description of the hypothetical systems seems to have all the right pieces, but put together in slightly the wrong order. There are no comments from Shklovskii in the published proceedings, and no one else comes closer than Ginzburg to hitting the mark.

Nevertheless, the invention of X-ray binaries is nearly always attributed to Shklovskii (1967). The Russian and English version of the paper are not identical (the latter was the first-ever ApJ Letter published separately from the main Journal). The Russian one was submitted slightly later, and the quotes are from it (in translation).

Shklovskii envisions "a neutron star forming a comparatively massive component of a close binary system. A stream of gas flowing out of the second component is permanently incident on the neutron star... It is suggested that the optical object accompanying the x-ray source might be a cool dwarf star, with half of its surface heated by a strong flux of hard x rays from the source." Footnote 3 reports "The hypothesis that the source Sco X-1 is a close binary system, one of whose components is a neutron star, with the hot plasma in the neighborhood of the neutron star being formed through accretion of a gas stream flowing out of the normal component, was formulated by us during discussions at the Nordwijk syposium on August 28, 1966."

It is impossible to be sure whether "we" is a euphemism for "me" (implying that he had sat quietly thinking while the others were all talking around the correct concept) or is meant to be a sharing of credit with other participants. Burbidge (1972) retelling the story 5 years later, recalls additional participants (Savedoff, M. Burbidge Prendergast, and Herbig), but sheds no further light on the evolution of the model, again saying that "Dissipation of rotational energy of the system" was the source contemplated. Ginzburg's (1990) still later recollections add no new information, and he does Shklovskii something of an injustice by ignoring the footnote about Nordwijk.

Most remarkable of all is a paper (Novikov & Zeldovich 1966) submitted in late 1965 and accepted on 16 April 1966. One of three footnotes added in proof declares, "The baryon or hardened star can be a component of a double star. In this case it can be discovered by the perturbation of the other, normal star...In a double system, the accretion on the collapsed star is felt by the stellar wind from the normal star. It shall led (sic) to strong X-ray and γ-ray emission. In the case of accretion the falling gas is heated by a stationary shock wave and radiates like an optically thin hot layer (brehmsstralung) instead of the black-body radiation. The last investigations of Scorpius XR1 seem to be in accordance with this picture." Clearly they corrected their proofs some time after 16 April (and the journal issue did not reach library shelves until the end of the year), but it is impossible to be sure whether they had heard of either the optical identification or of the Nordwijk discussion when those words were written.

In either case, Zeldovich and his associates were in the best possible position to appreciate the significance of close binaries with compact components, for they had already begun a search (Guseynov & Zeldovich 1966; Zeldovich & Guseynov 1966) for "Collapsed Stars in Binaries" (meaning primarily black holes). The strategy was to examine known single-line spectroscopic binaries for ones where the orbit paramaeters suggested an unseen star more massive than the visible one. They found seven candidates for which "the hypothesis is put forward that the second unobserved star is a collapsed star, or, as in case 7, an old neutron star." X-ray emission is not mentioned, indicating that Sco X-1 had not yet come to their attention in November 1965. None of their candidates is now thought to harbor a compact component.

A few years later, Trimble and Thorne (1969), examining a much larger catalog of SBs, had a clearer idea of what to look for and summarized the situation as, "The absence of a secondary spectrum in these systems could, in principle, result from the secondary star's being either a collapsed star or a massive neutron star. For all these systems, however, other explanations are possible in the light of present observation. Statistical considerations suggest that few, if any, of the systems in these lists contain collapsed or neutron-star secondaries. None of these binary systems coincide with any published X-ray position." Given the size of pre-Uhuru error circles, this in itself borders on the surprising. Every couple of years, a serious binary star astronomer turns attention on one of these systems and finds that, indeed, other explanations are preferable, e.g. Wonnacutt et al. 1993 on IK Peg.

The last wrong paper on X-ray binaries seems to have been Cameron and Mock (1967) who preferred white dwarf accretors, on the grounds that gas hitting a neutron star would produce photons of excessive hardness (at one photon per protron they do, but thermalized over the surface at Eddington luminosity or lower, they do not)

4. BLACK HOLES, ACCRETION DISKS, AND GLOBULAR CLUSTER SOURCES

The first black hole "candidate" (see A.P. Cowley elsewhere in this volume) was Cyg X-1 (Gursky et al. 1971) and its optical identification HDE 226868 (Bolton 1972). The X-ray observers initially put it at about a kpc from us, on the basis of low-energy absorption and average ISM density, and Bolton at 2 kpc on the assumption that the visible star was a reasonably normal OB supergiant. He was, of course, right, but, as Cowley notes, the mass function for the system is relatively small, and the resulting compact mass therefore exceedingly dependent upon the assumed M_1. Thus arose the last fundamentally wrong paper on this subject (Trimble, Rose & Weber 1972), "A Low-Mass Primary for Cygnus X-1?", propounding the curious notion that "If the primary of HDE 226868 (Cyg X-1) is a low mass ($0.3 = 0.5\ M_\odot$), low surface gravity B star of the type of which the primary of HZ 22 is the prototype, then the secondary falls well within the mass range of stable neutron stars (and white dwarfs) and need not be a black hole." We were last because observers flocked instantly to their telescopes to trace out the reddening of HDE 226868 and the velocities of interstellar absorption lines in its spectrum, thereby firmly placing it at the larger distance and ruling out a low mass (and low luminosity) primary. This is the only paper with which the author has ever been involved that was in print before the postcard acknowledging receipt came. This accounts for the misspelling of Mal Ruderman's name in the text, for which we belatedly apologize to him.

The significance of accretion disks and accretion luminosity was first appreciated in the context of cataclysmic variables. Crawford and Kraft (1956) wrote of AE Aquarii, "If, in fact, as the foregoing considerations suggest, mass is accreted by the blue star at a rate of the order of 10^{25} g/year, we would expect that the kinetic energy of the tenuous infalling material would be dissipated into heat by viscosity in the turbulent motion and by impact with the denser matter of the star's atmosphere. The heat thus liberated should appear as a contribution to the luminosity of the blue star of about the amount $L = GM\sigma R^{-1}$," where σ is the accretion rate. With M and R appropriate to a white dwarf, they thereby account for the blue, non-stellar luminosity of the system. Accretion is explicity from a ring or disk where, "The velocity gradient will cause a very rapid turbulent exchange of angular momentum, so that the inner part of the ring will lose angular momentum and move in closer, while the outer part gains angular momentum and spreads out...and the net effect is that matter accretes onto the surface of the blue star, which acts as a sink for the angular momentum as wel." The rate of mass transfer is found independently from a model of the expansion of the K donor and from recombination of hydrogen. That all three agree the authors (righly) regard as strong support for the model. We can only regret that neither Crawford nor Kraft was at Nordwijk!

Application of spherical accretion to the powering of active galaxies came later (Salpeter 1964; Zeldovich & Novikov 1964) and disk accretion in that context (Lynden-Bell 1969) and for X-ray binaries (Prendergast and Burbidge 1968) still later.

One globular cluster X-ray source predates the Uhuru catalog. A rocket flown by NRL on 25 April 1965 recorded a source which they called SGR XR-4. Called L16 by the Lockheed group, whose rocket flew on 30 September 1965, it is now catalogued as 4U 1820-30 and sits near the center of NGC 6624, though no one knew this for several years thereafter (Seward 1970 and pr. comm.). The 3U catalog, submitted in August 1973, included two firm and one possible globular cluster IDs. Who should be credited with first noticing that this is far more than the clusters' fair share is nearly lost in the mists of folklore. E. van den Heuvel (elsewhere in this volume) remembers hearing it from H. Gursky at a July 1973 meeting in Cambridge UK (Physics and Astrophysics of Compact Objects). According to my lengthy and still extant notes from that meeting, Gursky's public talks discussed properties of a number of individual sources, but not the globular cluster ones, while J. Ostriker remarked that there seemed to be X-ray sources in globulars, but did not mention an excess (He also asked rhetorically whether the clusters contain U Gem stars, which have similar orbit periods to the XRBs then known, an issue not fully resolved to the present time, J. Grindlay elsewhere in this volume). In his remarks here, Gursky expressed doubts about ever having gotten around to publishing the point. It appears, however, in the printed version of a February 1974 talk (Gursky & Schreier 1975). At least three other sets of notes from the 1973 meeting probably exist, and there is, therefore, some hope still of determining whether this bit of history now incorporates a Dyson error of the first kind or of the second!

5. AFTERTHOUGHTS

The oral version of this presentation decribed the historical period under consideration as Paleolithic, or pre-Dutch. But in fact the scenario for X-ray binary formation described by van den Heuvel in 1973 used as one input statistics of main sequence binaries compiled by Kuiper (1935). There was, in other words, no pre-Dutch period. My notes from that talk include the gloss "what is this for Batten's Catalogue" next to Ed's choice of mass-ratio distribution. The answer (Trimble 1974) disagreed with what Kuiper had found, and was the precursor of a binary-system-mass-ratio-statistics cottage industry that now produces about a dozen papers per year. And I was probably wrong again (Duquennoy & Mayor 1991)

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