Final Report

Summary of Objectives, Approach, Results, Conclusions, etc.**Abstract**

Our objectives included 1) The confirmation of the 2.1 ms candidate for the pulsar (PSR1987A) in Supernova 1987A (SN1987A), and, *provided the candidate is real (and if it is real, we have successfully tracked its frequency for two years)*, 2) to determine the nature of its spindown, including whether it is a result of gravitational radiation (GR), inertia transfer associated with differential rotation, changes in the moment of inertia, or the affects of a wide binary system.

The approach we used was to monitor SN1987A year-round with large and small telescopes and attempt to dig the faint candidate out of the noise. In order to extend the season of observation, we enlisted the help of observers at the 1-m University of Tasmania telescope.

We have decent results to support the supposition that the spindown of this candidate for PSR1987A is indeed due almost entirely to gravitational radiation. The observations with the University of Tasmania 1-m telescope were successful in detecting the 2.1 ms candidate pulsar on at least three occasions. The ~1,000 s precession period has been confirmed at both the large and small telescopes.

We can conclude that there is now little doubt that SN1987A was the result of a merger of two giant stars which resulted in: 1) The ejection of the three rings during a common-envelope/Roche lobe overflow phase which may have lasted only 300 to 1,000 years some 30,000 years ago, 2) The extreme mixing of the elements during the spiraling in phase of the two ~0.7 solar mass white dwarf cores, 3) The blue supergiant nature of the progenitor star, Sk -69 202, and 4) the formation of a weak-field ms pulsar spinning every 2.1 ms.

The importance of this finding is nearly inestimable. We now know that neutron stars can sustain or grow oblatenesses of 5 parts in ten million some 5-7 years after their explosive birth, and that pulsars born in such a way can outshine all other compact solar mass type objects by an order of magnitude in nearly pure gravitational radiation. We know now that most weak field ms pulsars are born in such core mergers, which explains their drastic overabundance in the globular clusters relative to the low mass X-ray binaries, which were previously, and erroneously thought of as their progenitors. We now know that such objects are potentially detectable as gravitational sources by detectors which may be constructed during the next decade.

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The Confirmation of the 2.1 ms Candidate for PSR1987A. and the 1000-hour Arecibo Piggyback ms Pulsar Survey

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I. Introduction (Background and Approach)

Supernova 1987A is now over 7.5 years old and one of the great enigmas of the end of this century. The neutrinos observed guaranteed the formation of a neutron star, yet the optical remnant has faded far beyond the point at which it could be hiding a luminous pulsar like that found within the Crab Nebula. By detecting and monitoring the pulsar remnant of this supernova, we were able to unravel the mysteries surrounding its birth.

II. Progress During the Reporting Period

A. Major Findings

We have detected and monitored the usually faint, but sometimes bright, 2.1 ms optical pulsations from SN1987A for 2.5 years now. The pulsations are frequently observed to be modulated with a $\sim 1,000$ s period which can not possibly be due to planets because of their very complicated nature, including strong amplitude modulation components. However, the modulation mimics a time-like ephemeris on rare occasions. The pulsations are slowing down at the unheard of rate of $20 - 35 \mu\text{Hz/day}$, which implies a tremendous luminosity. In an effort to extend our monitoring of this candidate to all year round, we have enlisted the help of Kym Hill and Robert Watson of the University of Tasmania with their 1-m telescope located at the very southerly latitude of nearly 43° south. Their first three observations were detections. Moreover, two out of three observations with the Hubble Space Telescope High Speed Photometer (ripped out of the HST last December) which were used as the basis of an upper limit telegram which appeared in late May of 1993, showed definite evidence for the 2.1 ms pulsar. The pulsar subsequently faded over the next year, so that we really only detected it consistently with the largest telescope (the CTIO 4-m).

B. Conclusions

If we realistically examine the possibilities for what type of compact remnant lies within the now faint ember of SN1987A, the most *conservative* possible evaluation of this possibility is that it contains a weak-field ms pulsar. Certainly, a strong-field pulsar spinning at dozens of Hz is excluded as the remnant is obviously not strongly glowing. In addition, there is no need to "inject" any population of slow pulsars (Lorimer et al. 1993), so a slow pulsar in SN1987A is unlikely. A black hole for the compact remnant of SN1987A requires the post SNa accretion of a substantial fraction of solar mass, and thus strains credibility. If, on the other hand, a weak-field ms pulsar lies within SN1987A, then there is no energy problem, as such an object could easily be less luminous than 5×10^{36} ergs/s, even with an effective black body surface temperature of 3 keV (and most estimates put this over a factor of ten lower).

It is becoming increasingly clear (Chen and Colgate 1994) that all of the details of SN1987A can be easily explained as a core-collapse and subsequent explosion which resulted from the merger of the degenerate cores of two massive stars in close binary system. The rings were formed during a common envelope phase in which material was pushed out through one, or even both, outer mass axis Lagrangian points, as well as blown tangentially off the surfaces of the stars facing one another in the two directions normal to the orbital plane. This phase which involved the overfilling of the stellar Roche equipotentials lasted only about 300 - 1000 years, and took place only 30,000 years ago. The merger also naturally explains the severe mixing observed in the ejecta, and the blue supergiant nature of the progenitor star. Finally, the model predicts that the precursor merged pre-supernova degenerate core will spin with a period of 1.98

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s (determined solely by the Jacoby/Maclaurin instability branch point), and that the resulting pulsar will be a weakly-magnetized neutron star spinning with a period near 2.1 ms. The question which remains is: Does the means by which this pulsar was born (rapidly rotating core merger) somehow guarantee that the infant neutron star will have a large quadrupole moment, while the more usual method of birth (a single core collapse within a red giant star) does not? We can imagine the core collapse of the merged white dwarf possibly maintaining some sort of bar instability all the way down to the neutron star, where it establishes itself as a non-Maclaurin oblateness. It may take another two nearby supernovae and subsequently discovered pulsar remnants within them to actually settle this question. *This may take another 300 years!* In addition, the only other "young" ms pulsar, the 3 ms psr in the globular cluster, M28 (Lyne et al. 1987), is also above the "spin-up" line on the period-period time derivative plane in the same general location as this candidate for PSR1987A, indicating that it too, could be spinning-down partly due to GR.

The other insights this explanation gives us are numerous indeed. Globular clusters generate their many ms pulsars by the core mergers resulting from the numerous binary-binary collisions, necessary before the cluster can undergo core collapse (Chen and Leonard 1993). Their ms pulsars are, for the most part, born fast, at least until after cluster core collapse, at which time, weakly-magnetized neutron stars can be spun up by accretion from a newly-acquired binary companion (Chen, Middleditch, and Ruderman 1993). This gets us out of the previously awful problem of explaining why there are so many ms pulsars, while there are so few Low Mass X-ray Binaries (LMXB's), which were previously thought of as the progenitors of the ms pulsars. It is no accident then, that all ten of the ms pulsars known in 47 Tuc (Manchester et al. 1991), a pre-core collapse cluster, have spin periods between 8 and 2.1 ms -- these were all born fast. Nor is it unexpected that, of the eight known pulsars in M15 (Middleditch et al. 1993), four have periods longer than 30 ms, while the other four have periods shorter than 7 ms -- four were born fast, while the slower four were "spun up". Those which were spun up, did not reach nearly the insane rotation rates characteristic of the two Galactic objects 1937+21 and 1957+20, which have periods near 1.6 ms, because there was less material to accrete in the globular cluster environment (the stars forming the post core-collapse binaries, are, after all, at most about 1.5 solar masses, whereas there is no upper limit on the mass for the progenitors of the Galactic objects).

Now for the details of the candidate for PSR1987A. The one effect, other than the origin of the gravitational quadrupole moment, which begs explanation for this candidate, is how it could possibly be an optical pulsar, unlike any other weak-field ms pulsar (at times it was near 21st magnitude, brighter even than the Crab pulsar would be at the distance to the LMC in this same band).

The decline of the frequency of the 2.1 ms pulsar candidate in SN1987A is evident in Fig. 1. With a spin rate of nearly 467.5 Hz, the implied energy of such a spindown (nearly 3×10^{10} Hz/s at times) is a factor of 1000 in excess of what the now faint SN1987A remnant can allow for electromagnetic radiation (almost 2.5×10^{39} ergs/s, most of which would be stopped and reprocessed by the remnant), and an order of magnitude greater than the total luminosity of the Crab pulsar. This leaves the possibility of inertia exchange of differential spins, a changing moment of inertia, an acceleration due to a wide binary system, or gravitational radiation (GR).

If the pulsar is spinning down due to GR, then it must have a gravitational quadrupole moment, i.e., an oblateness of some kind (5 mm out of 10 km) sustained *after five to seven years* in material about a hundred trillion times as dense as water in a gravitational field 100 billion times that at the Earth's surface. A possible cause other than a frozen remnant of a bar instability, would be a magnetic field with a strength of some 2×10^{14} Gauss buried under the surface of the crust, or even the material strength of the superdense lattice of the crust itself.

As nearly 99.9% the PSR1987A candidate spin-down can not be due to electromagnetic processes, the implied magnetic field can not greatly exceed 1.5×10^9 Gauss. With a 2.1 ms rotation period, the light cylinder is only about 10^7 cm, or 10 stellar radii. For this configuration, the relativistic γ factor is ten and the magnetic field at the light cylinder is only

about 1.5×10^6 Gauss. Thus the relativity-enhanced cyclotron frequency at the light cylinder, $\gamma^2 eB/mc$, corresponds to radiation of wavelengths near 7,500 - 15,000 Å. Thus, should pair production occur in the gaps near the light cylinder, radiation of the same wavelength will be produced. Since the neutron star should still be hot, and emitting X-rays, pair production will occur between these and the GeV γ -rays present, to some degree, in all pulsars. Moreover, it has been suggested that, given this candidate's location on the P - Pdot plane, it may *never* be a radio pulsar!

In addition, if the neutron star is oblate, then, unless the spin axis is exactly aligned with the axis of the quadrupole moment, then it *must* precess, with a precession period on the order of 4,000 s (or about 1,000 s if only the crust undergoes the precessional motion, as it only has about 25% of the moment of inertia of the whole star). Figure 1 also shows the time history of the candidate precessional period, which started near 24 minutes, declined to under 16 minutes before something apparently "broke" within the star after which time it rebounded to a value slightly longer than 1,000 s, which seems to be slowly relaxing, while, at the same time, the rate of decline in the *spin* period decreased.

This behavior -- the rate of decline of the spin period being inversely proportional to the precession period -- is exactly what is expected if both the precession and spindown via gravitational radiation are caused by the same non-Maclaurin oblateness of the neutron star, with a value of some 5 parts in 10^7 .

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Figure 1. The magnitude, pulse frequency, and modulation period (probably due to precession) for the 2.1 ms candidate pulsation in Supernova 1987A are plotted vs time since 1992. The results from the HST and University of Tasmania are broad band, S20 magnitudes, while the latest results from LCO and CTIO were broadband magnitudes for the V, R and I longpass. Earlier results from LCO and CTIO were derived with an 800 nm longpass filter (essentially an I magnitude). The latest detection from HST data taken on 06Mar93 is also plotted.

C. Equipment Obtained and Facilities Used

a-b. Facilities at Los Alamos and other campuses

We have made steady progress with the Rockwell Solid State Photomultiplier (SSPM). During the last observing run in Feb. 1994, it had a quantum efficiency near 1%. This has been subsequently improved to about 4%, and is now getting useful in the monitoring of SN1987A for pulsations.

The resources of the Los Alamos Integrated Computing Network (ICN) were used in the reduction of data from SN1987A. Fazio and Eikenberry can now do 134,217,728-point FFT's in about 8 hours using their SPARC and disk (on the ICN machine gamma, this goes in about 3 minutes including all analysis phases). The CM-5 of the Los Alamos Advanced Computing Laboratory (ACL) should be used for frequency-frequency derivative searches on large data sets from SN1987A, as the candidate may persist in being faint, or may not be real at all, necessitating a search for the real candidate. The local convolutions needed by such searches should go very fast. A set of about 16 billion-point transforms was done in a frequency-frequency derivative search on the Dec. 1993 CTIO 4-m data as a benchmarking testing during the checkout period for ICN machine gamma. More need doing, which is why we are now involved in writing an out-of-core FFT for the CM-5. *These facilities are essential to the execution of the proposed searches.*

Most of the software to reduce these volumes of data has already been written and tested. The software is also being constantly improved.

c. Other Facilities

As mentioned above, we will use the facilities of the two observatories in Chile, the Cerro Tololo Inter-American Observatory (CTIO) and the Las Campanas Observatory (LCO), as well as the facilities of Mt. Stromlo and Siding Springs Observatories, Parkes, Arecibo, NRAO-Greenbank, the Very Large Array, and Lick Observatory. The PI is collaborating with other observers to observe with a time- and position-sensitive detector which is fielded at the European Southern Observatory. CTIO is part of the National Optical Astronomy Observatories (NOAO), which is run by the Association of Universities for Research in Astronomy (AURA), of which the University of California is a founding member. The Las Campanas Observatory is run by Caltech and the Carnegie Institution of Washington. Arecibo Observatory is run the National Astronomy and Ionosphere Center of Cornell University.

D. Tangible Results

(Renewal Proposals Only)

Ransom left Fazio for the Army, as planned, he should have his masters. Deich finished his Ph.D. and went going to Dwingeloo, while Navarro has likewise finished, and landed at the VLA. Eikenberry is a new student of Fazio's. Vasisht is still a graduate student of Kulkarni.

Papers

Refereed Journal Articles Published

Chen, K., Middleditch, J., and Ruderman, M., Low Mass X-ray Binaries and millisecond pulsars in globular clusters, *Ap. J. (Letters)*, **408**, L17, 1993.

Deich, W. T. S., Middleditch, J., Anderson, S. B., Kulkarni, S. R. Prince, T. A., & Wolszczan, A, The binary pulsar 1908+00 in NGC6760, *Ap. J.*, **410**, 95 1993.

Imamura, J. N., Middleditch, J., Scargle, J. D., Steiman-Cameron, T. Y., Whitlock, L. A., Wolff, M. T. and Wood, K. S., The Quasi-Periodic Oscillations of VV Puppis, *Ap J.*, **417**, 793, 1993.

Refereed Journal Articles Submitted

Ransom, S. M., Fazio, G. G., Eikenberry, S. S., Middleditch, J., Kristian, J., Hays, K., and Pennypacker, C. R., High Time Resolution Infrared Observations of the Crab Nebula Pulsar, submitted to the *Ap. J.*

Refereed Journal Articles in Preparation

Middleditch, J., S. R. Kulkarni, W. T. S. Deich, S. B. Anderson, T. A. Prince, and A. Wolszczan, Discovery of a 4 ms pulsar in M15, to be submitted to *Nature*, 1992.

Ray, P. S., Deich, W. T. S., Kulkarni, S. R., Prince, T. A., Thorsett, S. E., Vasisht, G., Wolszczan, A., Backer, D. C., Holliman, J., and Middleditch, J., Much Ado about Nothing: Several Large-Area Surveys for Radio Pulsars from Arecibo, in preparation, 1994.

Refereed Journal Articles Written, Pending Submission

Middleditch, J., Kristian, J. A., Kunkel, W. E., Sasseen, T. P., Pennypacker, C. R., Muller, R. A., Perlmutter, S., Lucinio, R., Imamura, J. N., Steiman-Cameron, T. Y., Fazio, G. G., Ransom, S., and Eikenberry, S. S., Discovery of a 2.1 millisecond pulsar in Supernova 1987A, to be submitted to *Nature*, we hope before Heat Death overtakes the Universe. This paper is available on anonymous ftp to 128.165.21.64 in the dir "pub/jon" as "paper.tex". The last few lines explain how to get the figures. Some of these may have been compressed and taken on a ".Z" suffix.

Middleditch J., Hill, K. M., and Watson, R. D., Rapid Photometry of the 2.1 millisecond optical pulsar in Supernova 1987A, to be submitted to *Nature*, again, maybe prior to recollapse. It is also available by anonymous ftp to 128.165.21.64 in the dir "pub/jon" as "tas.tex". The last few lines explain how to get its figures. Some of these may have been compressed and taken on a ".Z" suffix.

Other Publications Published

Middleditch, J., Deich, W. T. S., Kulkarni, S. R., and Wolszczan, A., Discovery of 4 and 7 ms pulsars in M15 (F & H), B. A. A. S., 24, No. 4, 1275, 1993.

Other Publications in Preparation

Middleditch, J., The time measure in astronomy, for the Italian SET encyclopedia, supposedly 40,000 words, or some 60 pages. In the final phases of completion.

Presentations

Middleditch, J. Parallel Fourier Transforms, at the 1994 Computational Science Workshop, held at the University of New Mexico, August 3rd, 1994.

Middleditch, J., The status of pulsars searches in Supernova 1987A, at the Ninth New Mexico Symposium on Astrophysics, Array Operations Center, NRAO, Socorro, NM, Oct. 29, 1993.

Middleditch, J., The discovery of 4 and 7 ms pulsars in M15 (F & H), at the 189th meeting of the American Astronomical Society, Phoenix, AZ, Jan.

E. Intangible Results

1. New Capabilities

As mentioned above, the SSPM now seems to have a qe of nearly 4%. In a few years, with the development of the edge-on chip, the qe should rise to the dozens of percent.

2. Collaborations and Contacts

As a result of this work, a group at University College, Galway has invited us to collaborate on observations of SN1987A with their time- and position-sensitive detector. This detector is similar to the RULLI detector used by NIS-2, and this work should strengthen the Laboratory's mission with this effort.

III. Future of the Project

As many of the collaborators as possible will meet in Pasadena during the week of the 19th-23rd of September, 1994, in order to discuss our future plans, which, I hope, will include submitting the two papers on the 2.1 ms candidate. Last year, when I pushed for some form of publication, some of these same collaborators threatened to *die*. We will also discuss plans to continue observing SN1987A.

Who will use these results? Should the 2.1 ms candidate turn out to be real, everyone in Astronomy and Physics will benefit. It will breath life into the gravitational observatories. Hans Bethe will keep his hands off the nuclear equation of state, and everyone will further benefit. One of the side effects of working in this field, is that we have to solve a lot of problems about data with a very low signal-to-noise ratio. So aside from the widespread scientific usefulness of knowing just how many ms pulsars there are in the Galaxy, and how they form, and how supernovae explode, etc. etc., there is also the very widespread application of the mathematical techniques being developed.

We will also pursue our observations of the LMC supernova remnant by other than ground-based optical observations, such as X-ray and γ -ray observations from balloons and satellites, and optical observations with the Hubble Space Telescope, and Infrared observations with SIRTf. These observations will be funded, at least in part, by other agencies.

The LANL PI has done this research for almost 23 years now, and has never run out of targets of opportunity. The possibilities of this Universe are truly infinite, and we will certainly never lack for exciting observations.

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