THE ASTROPHYSICAL JOURNAL, 267:L77–L81, 1983 April 15

STELLAR COLLAPSES IN THE GALAXY

JOHN N. BAHCALL
Institute for Advanced Study,[1] Princeton, New Jersey; and Weizmann Institute, Rehovot, Israel
AND
TSVI PIRAN
Racah Institute for Physics, Hebrew University, Jerusalem, Israel; and Institute for Advanced Study, Princeton, New Jersey
Received 1982 November 1; accepted 1982 December 17

ABSTRACT

The expected rate of stellar deaths in the Galaxy (~ 0.1 per year) is computed using a detailed model of the distribution of stars in the disk and standard values for Population I stellar evolutionary lifetimes. Some of the uncertainties in this calculation are described. The sensitivities to stellar collapse of the existing gravitational wave and solar neutrino detectors are expressed in terms of convenient astrophysical variables and are found to be comparable for conventional choices of collapse parameters. The fraction of stars in the Galaxy that are accessible to a detector—of any kind of radiation (including X-ray or γ-ray satellites or ground-based telescopes)— that can survey out to a given distance is tabulated for different maximum distances and is shown to be important for interpreting the capabilities of existing detectors. The results of Davis provide the best available upper limit on the collapse rate. At least one order of magnitude improvement in the sensitivity of solar neutrino or gravitational wave detectors is necessary in order to detect galactic stellar collapses at the rate predicted by current models.

Subject headings: galaxies: Milky Way — gravitation — neutrinos — stars: collapsed

I. INTRODUCTION

Neutrinos and gravitational radiation both escape relatively easily from collapsing stars, and both signals have often been proposed as possible means of detecting otherwise unobservable stellar collapses. In this *Letter*, we compare the sensitivity to stellar collapses of the only operating solar neutrino experiment (Davis 1978) with the sensitivity of existing detectors of gravitational waves (see, e.g., Blair 1983). We compute the fraction, $q(R)$, of stars in the Galaxy that are accessible to a detector that can survey out to a given maximum distance, R, and show that this fraction is important for understanding the capabilities of the current detectors. This function is also useful in interpreting experiments with different kinds of detectors—sensitive to X-rays, γ-rays, radio waves, neutrinos, gravitational radiation, or any other kind of radiation—that detect events from a limited part of the Galaxy.

We infer, by analyzing the available data, an upper limit to the rate of stellar collapses in the Galaxy. This limit is of astrophysical interest because many collapses might occur in dense molecular clouds or other environments from which electromagnetic radiation cannot escape, and thus the collapses may not be detectable by more conventional observations (see also the discussions of uncertainties in inferred pulsar and supernova occurrence rates by Taylor and Manchester 1977; Tammann 1978; and Arnett 1979). The upper limit we infer from the available observations is an order of magnitude larger than the theoretical rate of observable stellar collapses we calculate using a detailed model of the stellar content of the Galaxy (Bahcall and Soneira 1980), the lifetimes of stars determined by conventional stellar evolution codes (see, e.g., Iben 1967; Alcock and Paczynski 1978; Becker 1981), the sensitivities of the operating detectors, and an optimistic scenario (see below) for stellar collapse. A more conventional scenario for stellar collapses leads to a predicted detection rate that is two orders of magnitude below the current observational limit.

II. DETECTORS

In order to compare the sensitivities of the two kinds of detectors, neutrino and gravitational, we first define effective confidence levels for positive detection that are intended to correspond very roughly to a 95% confidence of detection.

The chlorine solar neutrino detector (Davis 1978) has an approximately constant background flux of 2 solar neutrino units (SNU) (1 SNU = 10^{-36} captures per target atom per second), which may be due to solar neutrinos, cosmic rays, or other sources of noise with

[1] Permanent affiliation.

which collapse events have to compete. There are about 45 measurements of the production rate during the past decade (Davis 1978, 1982). Only once was the capture rate in the tank of chlorine as large as 6 SNU. In fact, it has been pointed out (Bahcall 1977, 1978) that this high run is consistent with the occurrence of a stellar collapse in the Galaxy in the later half of 1977. On the basis of the above results, we assume here that a flux level of more than 6 SNU is necessary in order to achieve an approximately 95% confidence of detection in the chlorine tank.

The integral over time of the neutrino capture rate from a stellar collapse event is expected to be (characteristic quantities in parentheses, see Brown 1977; Bahcall 1978):

$$\sum_i \Phi_{\nu_i}\sigma_{\nu_i}(^{37}\mathrm{Cl}) = 3.0 \times 10^{-30}\left(\frac{M_\nu}{0.14\,M_\odot}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)^{-2} \times \left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)^{-1}\left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)^{3.7}. \quad (1)$$

A rest mass, M_ν, is assumed emitted in the form of electron neutrinos. The cross section for 10 MeV neutrinos on ^{37}Cl is about $2.3 \times 10^{-42}(E_\nu/10\ \mathrm{MeV})^{3.7}$ (Bahcall 1978). The symbol denotes an average over the emitted neutrino spectra. The required signal for 95% confidence detection in the current experiment is 2×10^{-29} captures per atom of ^{37}Cl, which is equivalent to 6 SNU assuming that the collapse occurs at the beginning of a 1 month observation with the solar neutrino detector. The minimum required capture rate is proportional to $\{\exp[t(\text{process})/t(\text{mean lifetime})] - 1\}^{-1}$.

The gravitational radiation detectors are metallic (or crystal) resonant bars that are monitored for vibration in a given mode, usually around 1 kHz (Blair 1983). Laser interferometer detectors are constructed now, but these are not active yet. The bar detectors are narrowband detectors, whose response depends on $\varepsilon(\nu)$, the integrated energy flux at the detector's resonance frequency. It is convenient to measure $\varepsilon(\nu)$ in units of GPU (1 GPU = 10^5 ergs cm^{-2} Hz^{-1}). For an impulsive pulse, $\Delta\nu \sim \nu$; and

$$\varepsilon(\nu) = 0.01\left(\frac{M_{\mathrm{gr}}}{0.014\,M_\odot}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)^{-2}\left(\frac{\Delta\nu}{1\,\mathrm{kHz}}\right)^{-1}\mathrm{GPU}, \quad (2)$$

where M_{gr} is the rest mass radiated as gravitational radiation. This estimate assumes that the sources are isotropic; it includes a factor of 0.5 due to the two different modes of polarization. For anisotropic sources, a fraction, f, of the sources will emit, in our direction, a signal which is $1/f$ times as strong. As long as the detection range is such that we detect a fraction less than f of the events in the Galaxy, this effect will increase the overall observed event rate.

It is sometimes useful to discuss gravitational radiation experiments in terms of the strain amplitude, $\Delta l/l$ (see, e.g., Press and Thorne 1972; Thorne 1980); $\Delta l/l$ is related to $\varepsilon(\nu)$ as (Weiss 1979; Tyson and Giffard 1978)

$$\left(\frac{\Delta l}{l}\right)^2 = \frac{2\pi G}{c^3}\left(\frac{\Delta\nu}{\nu}\right)(\nu\tau_p)^{-1}\varepsilon(\nu), \quad (3)$$

where τ_p is the pulse duration (usually $\tau_p \sim 1/\Delta\nu \sim 1/\nu$). With the above "nominal" parameters and assumptions, $(\Delta l/l) \sim 4 \times 10^{-18}$. The noise level in the best current detector (Boughn *et al.* 1982; Michelson 1983) is about 10^{-2} GPU. The integration time of this detector is of the order of 1 s. There are about 3×10^7 possible measurements per year, and this leads to a threshold of 0.06 GPU for the stated confidence level (assuming that the detector is operating without interruption for the entire year).

The ratio of mass (energy) that is emitted in the form of neutrinos, M_ν, to the amount emitted in gravitational radiation, M_{gr}, is an important parameter for comparing the sensitivity of neutrino and gravitational detectors. For convenience, we define the quantity:

$$C \equiv \left(\frac{M_\nu}{M_{\mathrm{gr}}}\right). \quad (4)$$

Crude astrophysical estimates of the efficiencies suggest that $C \gtrsim 10$, with at least 10 times as much energy radiated in neutrinos as in gravitational radiation (see, for example, Brown 1977; Bahcall 1978; Smarr 1979; Saenz and Shapiro 1978, 1979, 1981; Eardley 1983, and references therein). However, this parameter is very uncertain and is one of the crucial theoretical quantities to be estimated in future, more realistic theoretical calculations. For a fixed M_ν, suggested by the Arnett-Paczynski collapse picture (see § III), $\varepsilon \sim C^{-1}$ and $(\Delta l/l) \sim C^{-1/2}$.

The sensitivities of current detectors, gravitational and neutrino, are comparable for C of the order of 10, with the choice of parameters that are suggested by equations (1)–(2). In making this comparison, we have assumed that all the neutrinos have an energy of 10 MeV (which underestimates the sensitivity since the tail of the distribution will increase the expected capture rate; see eq. [1]) and that the chlorine tank is processed every month (the *average* interval over the past decade has been more nearly 3 months). The detailed shape of the emitted neutrino spectrum and the actual frequency with which a chlorine tank would be processed are, of course, not known. We also assume that the gravitational detector is monitored without interruption and that its resonance frequency is within the frequency range of a typical pulse.

III. COMPARISON OF PREDICTED AND OBSERVED RATES

In order to compare the observational result with theoretical expectations, we need to compute the observable stellar death rate, $D(M_{\rm min})$:

$$D(M_{\rm min}) = N\int_{M_{\rm min}}^{\infty} dM \frac{q[R(M)]f(M)\Phi(M)}{T(M)}. \quad (5)$$

The sensitivity function, $q(R)$, is the fraction of stars in the galactic disk that lie within a distance R of the Sun. Numerical values for q were computed using the Bahcall and Soneira (1980) model of the Galaxy and are given in Table 1, along with an analytic approximation that is valid for small R. The total number of stars, N, is approximately equal to the number in the disk ($\sim 7 \times 10^{10}$); the number of massive spheroid stars is very much smaller. Also, $f(M)$ is the fraction of stars of mass M that produce a collapse of the type considered here, $\Phi(M)dM$ is the observed (McCuskey 1966; Luyten 1968; Wielen 1974) probability that a disk star has a mass between M and $M + dM$ (taking account of the known dependence of scale height on stars of mass M [Bahcall and Soneira 1980] and the disk mass-luminosity relations, eq. [17], same reference), and $T(M)$ is the evolutionary lifetime of stars of mass M. We assume, in using equation (5), that the distribution of stars in the Galaxy has remained approximately constant for the lifetimes (see below) of the stars giving most of the contribution to the integral. The function $\Phi(M)$ changes rapidly in the region of masses of interest (see, e.g., Fig. 1 of Bahcall and Soneira 1980), which necessitates a detailed numerical integration in order to obtain reasonable accuracy for the integral in equation (5).

We have used values of the stellar lifetimes for Population I stars that were computed by many different authors (see references and results in, e.g., Stothers 1966, Iben 1967; Alcock and Paczynski 1978; Becker 1981) for masses between 1 and $10^2\ M_\odot$, neglecting complications due to companions, composition variations, and rotation. The results may be fitted to a quadratic formula with a typical accuracy of the order of 10%:

$$\log_{10}\left[T(M)/10^6\ {\rm yr}\right] = 4.0 - 3.6\log_{10}(M/M_\odot) + 1.0\log_{10}^2(M/M_\odot). \quad (6)$$

For $M \gtrsim 10^2\ M_\odot$, $\log_{10}[T(M)/10^6\ {\rm yr}] \approx 0.3$.

We are interested in computing first the total rate of stellar deaths including the formation of neutron stars and black holes, supernova explosions, and other possible stellar disintegrations, but *excluding* the formation of white dwarf stars. For this broad class of stellar deaths, the lower limit, $M_{\rm min}$, in equation (5) has been estimated in recent work to lie in the range from 3 $M_\odot$ to 10 $M_\odot$, with 5 $M_\odot$ a popular value (see Paczynski 1970; Anthony-Twarog 1982, and references therein).

The *total* rate of stellar deaths predicted by stellar evolution theory and the Bahcall-Soneira (1980) model for the stellar content of the Galaxy is $D = 0.11^{+0.05}_{-0.02}$ yr^{-1}, assuming $f(M) = 1$ (and taking $q(R) = 1$ in eq. [5]). The intermediate rate was calculated assuming $M_{\rm min} = 5\ M_\odot$; the upper and lower values refer to the cases of $M_{\rm min} = 3\ M_\odot$ and 10 $M_\odot$ respectively. The contribution from stars with $M \gtrsim 20\ M_\odot$ is 0.04 yr^{-1}. If we extend the integral down to 1.4 $M_\odot$, then $D(1.4\ M_\odot) = 0.4$ yr^{-1}.

The results obtained by Davis (1978) using his solar neutrino detector are of unique value since they cover a longer observation period, namely a decade, than is available for any other comparable experiment. At most, one candidate stellar collapse was observed in the past decade, from which we conclude that the rate of collapses within the disk of the Galaxy, of the kind represented by the characteristic parameters of equation (1), is less than 0.1 per year. In the language of equation (5), the observations imply $D(M_{\rm min}) < 0.1$ yr^{-1}, when the proper sensitivity function, $q(R)$, is included. (The observations are also consistent with a much larger number of less energetic events, e.g., $\sim 10^2$ events per year with $M_\nu \approx 0.03\ M_\odot$.)

We compute two extreme values for the expected detection rate of stellar collapses in the existing ^{37}Cl solar neutrino detector. The lower predicted detection rate is based on the work of Paczynski (1970) and Arnett (1977*a*, *b*). According to their stellar evolution calculations, violent carbon combustion—but not a stellar collapse with emission of energetic neutrinos—is expected to occur for stars with masses less than about 10 $M_\odot$. Moreover, above 10 $M_\odot$ only about 0.14 $M_\odot$ of binding energy is available, practically independent of stellar mass, for emission as neutrinos or gravitational radiation. The appropriate sensitivity function, q, for

TABLE 1

FRACTION[a] q OF STARS IN THE GALACTIC DISK WITHIN A DISTANCE R OF THE SUN

R (kpc)	$q(\leq R)$	R (kpc)	$q(\leq R)$
1.0	0.003	10.0	0.53
2.0	0.012	12.0	0.68
3.0	0.028	14.0	0.79
4.0	0.056	16.0	0.87
5.0	0.10	18.0	0.92
6.0	0.16	20.0	0.95
7.0	0.24	25.0	0.98
8.0	0.34	30.0	1.0

[a]Calculated using the galactic model of Bahcall and Soneira 1980. For small $R \lesssim 3$ kpc, $q = 0.0028\ (R/1\ {\rm kpc})^2$.

this stellar evolution scenario is zero for $M < 10\ M_\odot$ and is independent of M for $M > 10\ M_\odot$. Over the past decade, the chlorine neutrino detector has been processed, on the average, about once every 3 months. For this case, $q \approx 0.0063$, corresponding to a maximum distance of detection, $R_{\rm max} = 1.5$ kpc.

For the Arnett-Paczynski stellar collapse scenario described above, the total expected detection rate is only 6×10^{-4} per year, two orders of magnitude less than the observational upper limit stated above.

The predicted rate of detection is uncertain for a number of reasons. One cannot be sure that the stellar evolution scenario described above is correct since it depends in an important way on one-dimensional time-dependent convection theory and since even the (in principle) simpler solar neutrino problem has not yet been solved. In calculating the expected detection rate, we have assumed that the locally determined stellar luminosity function is the same as the luminosity function averaged over the plane of the Galaxy; the luminosity function for massive stars is not well known even in the local neighborhood. Finally, we have assumed an average observation time for each run of 3 months.

We obtain an upper limit to the predicted detection rate by assuming that, for *all* stellar masses, 10% of the total stellar mass is emitted in the form of electron neutrinos. For this optimistic case, we find an expected detection rate of 0.01 yr (for all values of $M_{\rm min}$ between $3\ M_\odot$ and $10\ M_\odot$). This rate is still an order of magnitude smaller than the present observational limit.

Cleveland and Davis (1982) have pointed out that it would be relatively easy to build a larger ^{37}Cl solar neutrino detector and to operate it at a greater depth than the present mine experiment; the signal-to-noise ratio would be improved in the larger detector. The fluctuations in the steady signal that would be observed cannot be predicted with confidence since one cannot be sure of the origin of all the fluctuations that have been observed in the present detector. Nevertheless, it seems very likely that a larger detector would have an effective detection threshold for collapse events of no more than 3 SNU (instead of the 6 SNU for the present detector). For a detection threshold of 3 SNU, the expected rate of observable stellar collapses is 0.001 yr^{-1} (pessimistic case, see scenario above) to 0.025 yr^{-1} (optimistic case).

Making the same approximations as in Hampel (1980), we estimate a capture rate in the proposed gallium solar neutrino experiment (Bahcall *et al.* 1978; Hampel 1981) of (0.001–0.01) yr^{-1}. This rate is an overestimate since it assumes that extraction of ^{69}Ge can begin a few days after a collapse has been observed by other methods. However, most of the collapses will not be observable with photon detectors, making the early-warning problem difficult.

In summary, the existing chlorine solar neutrino detector, as operated over the past decade, would not have revealed stellar collapses if they occur at the rate and with the strength predicted by current models of stellar collapse and of the distribution of stars in the Galaxy. The predicted rate is two orders of magnitude below the observational upper limit for the standard (pessimistic) scenario of stellar collapse and one order of magnitude below the rate predicted using the most optimistic collapse scenario. These predictions are based upon an assumed average interval of 3 months between successive purges of the detector. If the tank were processed once a month, $q(R_{\rm max})$ would be increased by almost a full order of magnitude—from $q_{3\,\rm months} = 0.0063$ (for $R_{\rm max} = 1.5$ kpc) to $q_{1\,\rm month} = 0.046$ (for $R_{\rm max} = 3.7$ kpc). Purging the tank once a month would raise the predicted sensitivity of the existing detector to the level of the most optimistic stellar collapse scenario (particularly if one takes account of the likely increase in sensitivity arising from neutrinos with energies above 10 MeV).

The expectations for gravitational wave detectors are especially uncertain because of the difficulty in reliably computing the average amount of gravitational radiation emitted in stellar collapse, which—unlike the neutrino emission—is expected to be only a small fraction of the stellar binding energy. We assume here that the gravitational detectors are monitored continuously, with a duty cycle of approximately unity. For an optimistic estimate, $M_{\rm gr} = 0.014\ M_\odot$, corresponding to $C = 10$ (eq. [4]) and $R_{\rm max} = 4$ kpc (eq. [2]), we find $q(R_{\rm max}) = 0.056$. For the standard collapse scenario and galaxy model, these values correspond to an expected rate of 0.005 yr^{-1}. If $M_{\rm gr} = 0.001\ M_\odot$, then $q = 0.0045$ and the expected rate of detections is only 0.0004 yr^{-1}.

A moderate increase in sensitivity corresponding to a factor of 20 in $\varepsilon(\nu)$ (a factor of 4.5 in $\Delta l/l$) would, on the basis of the optimistic hypothesis, permit gravitational wave detectors to monitor 90% of the stars in the Galaxy—instead of the 6% currently accessible. Continuous monitoring with an improved detector having a threshold sensitivity of $\varepsilon(\nu) = 0.0005$ GPU would provide important new information on the collapse rate of stars in the Galaxy or the efficiency with which gravitational waves are produced by collapsing stars, or on both.

This work was supported by NSF grant PHY 79-19884, BSF grant to the Hebrew University, the Revson Foundation, and the Einstein Center for Theoretical Physics of the Weizmann Institute. It is a pleasure to thank D. Arnett, B. Cleveland, R. Davis, P. Hut, I. Iben, B. Paczynski, F. Shu, and R. Soneira for valuable comments and suggestions.

REFERENCES

Alcock, C., and Paczynski, B. 1978, *Ap. J.*, **223**, 244.
Anthony-Twarog, J. 1982, *Ap. J.*, **255**, 245.
Arnett, D. 1977*a*, *Ap. J.*, **218**, 815.
______. 1977*b*, *Ap. J. Suppl.*, **35**, 145.
______. 1979, in *Sources of Gravitational Radiation*, ed. L. Smarr (Cambridge: Cambridge University Press), p. 311.
Bahcall, J. N. 1977, *Ap. J. (Letters)*, **216**, 115.
______. 1978, *Rev. Mod. Phys.*, **50**, 881.
Bahcall, J. N., *et al.* 1978, *Phys. Rev. Letters*, **40**, 1351.
Bahcall, J. N., and Soneira, R. M. 1980, *Ap. J. Suppl.*, **44**, 73.
Becker, S. A. 1981, *Rev. Mod. Phys.*, **45**, 475.
Blair, D. 1983, *Gravitational Radiation*, ed. N. Deruelle and T. Piran (Amsterdam: North Holland), in press.
Boughn, S. P., *et al.* 1982, *Ap. J. (Letters)*, **261**, L19.
Brown, G. E. 1977, *Comments Ap. Space Phys.*, **7**, 67.
Cleveland, B., and Davis, R. 1982, private communication.
Davis, R. D. 1978, in *Proceedings of Informal Conference on Neutrino Physics and Astrophysics* (Moscow: F. I. Acad. Sci. USSR), Vol. **2**, p. 99.
______. 1982, private communication.
Eardley, D. N. 1983, in *Gravitational Radiation*, ed. N. Deruelle and T. Piran (Amsterdam: North Holland), in press.
Hampel, W. 1980, Max Planck Institute Report, Heidelberg (unpublished).
______. 1981, in *Neutrino 81*, ed. R. J. Cence, E. Ma, and A. Roberts (Honolulu: University of Hawaii High Energy Physics Group), Vol. **1**, p. 6.
Iben, I. 1967, *Ann. Rev. Astr. Ap.*, **5**, 571.
Luyten, W. J. 1968, *M.N.R.A.S.*, **139**, 221.
McCuskey, S. W. 1966, *Vistas Astr.*, **7**, 141.
Michelson, P. F. 1983, in *Gravitational Radiation*, ed N. Deruelle and T. Piran (Amsterdam: North Holland), in press.
Paczynski, B. 1970, *Acta Astr.*, **20**, 47.
Press, W., and Thorne, K. S. 1972, *Ann. Rev. Astr. Ap.*, **10**, 335.
Saenz, R. A., and Shapiro, S. L., 1978, *Ap. J.*, **221**, 286.
______. 1979, *Ap. J.*, **229**, 1107.
______. 1981, *Ap. J.*, **244**, 1033.
Smarr, L. 1979, in *Sources of Gravitational Radiation*, ed. L. Smarr (Cambridge: Cambridge University Press), p. 245.
Stothers, R. 1966, *Ap. J.*, **144**, 959.
Tammann, G., 1978, in *Supernovae*: *Proceedings of Astronomy Summer School 'E. Majorana, Erice, Sicily*, ed. J. Danzinger and A. Renzini.
Taylor, J. H., and Manchester, R. N. 1977, *Ap. J.*, **215**, 885.
Thorne, K. S. 1980, *Rev. Mod. Phys.*, **52**, 284.
Tyson, T., and Giffard, R. P. 1978, *Ann. Rev. Astr. Ap.*, **16**, 521.
Weiss, R. 1979, in *Sources of Gravitational Radiation*, ed. L. Smarr (Cambridge: Cambridge University Press), p. 7.
Wielen, R. 1974, *Highlights Astr.*, **3**, 395.

JOHN N. BAHCALL: School of Natural Sciences, The Institute for Advanced Study, Princeton, NJ 08540

TSVI PIRAN: Racah Institute for Physics, Hebrew University, Jerusalem, Israel