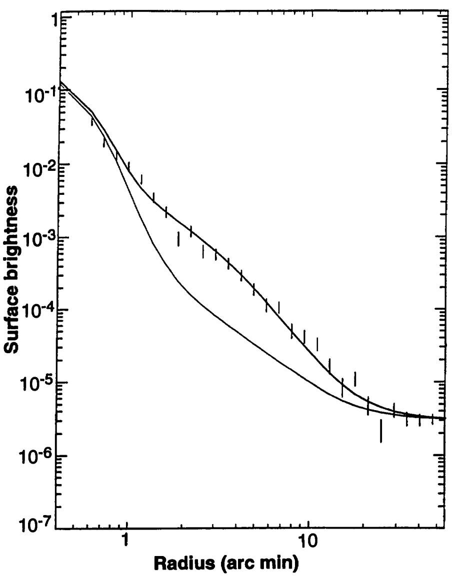

Fig. 4. Plot similar to Fig. 3 but for data from the ROSAT all-sky survey. In this case, the model PRF is averaged over the PSPC field of view. The fractional halo intensity after subtraction of the background is 27.7%.

telescope ground-calibration data. The difference between the measured and the modeled PRF is then considered as a halo around the source generated by the scattering on interstellar dust.

We also analyzed the data of GX 5-1 obtained during the ROSAT all-sky survey (Fig. 4). The resulting halo (fractional intensity = 27.7%) is absolutely consistent with the lunar occultation measurement. As a further proof, the individual count rates for the total flux (22.7 count s^{-1}), the halo flux (6.3 count s^{-1}), and the background count rate (6.8×10^{-5} count s^{-1} arc min^{-2}) within the selected spectral band pass around 1.65 keV are quite similar for all three data sets.

The consistency of the halo properties derived from the pointed observation data before and after egress and from the all-sky survey data demonstrate that the ROSAT telescope with the PSPC due to its very small mirror scattering and low background, respectively, is able to directly image dust-scattering halos and determine the dust properties along the line of sight. This result provides a solid basis for the analysis of the ROSAT all-sky survey data, where dust-scattering halos have been found around essentially every one of the highly absorbed, hard x-ray sources.

The angular extension of a dust-scattering halo is given by λ/a. For an average (spherical) dust grain with radius $a \sim 0.1$ μm and with a ROSAT-typical wavelength $\lambda \sim 10$ Å, the resulting halo sizes are of the order of half a degree. The properties of the grains as well as their spatial distribution can be derived from a halo analysis. For our (simplified) approach, we have fitted our data by single scattering on dust grains with sizes between 0.0003 and 0.3 μm, whereby the size distribution is described by $n(a) \sim a^{-3.5}$ (*7*). The dust is assumed to be distributed uniformly along the line of sight. The resulting scattering optical depth is $\tau \sim 0.3$, implying a dust column density of $\sim 3 \times 10^{10}$ cm^{-2} between GX 5-1 and Earth (*12*).

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High-Velocity Pulsars in the Galactic Halo

David Eichler and Joseph Silk

It is proposed that high-velocity pulsars are produced in extended galactic halos, and possibly in extragalactic space, from primordial (population III) stars. Such a population of neutron stars could provide an explanation for the gamma-ray bursters and would then accommodate the possibility that most bursters are not in the visible parts of galaxies.

A common origin is proposed for high-velocity pulsars and for gamma-ray bursters. This source is a subdominant population of neutron stars that are in a spatially extended halo around our galaxy. Theoretical speculations and especially recent observations suggest the possible existence of a halo population of neutron stars. Specifically, recent reports of diskward-moving, high-latitude pulsars and of a nearly isotropic distribution of gamma-ray bursters motivate us to propose a source of neutron stars in the halo. We suggest that neutron stars could form by mergers of white dwarfs.

We hypothesize that the halo contains dense clusters of relatively massive white dwarfs that formed at high redshift. Tidal captures and eventual expulsion of a common envelope plausibly produce closely spaced white dwarf binaries whose orbits slowly decay by gravitational radiation. We suggest that the mergers result in optically subluminous events as compared to ordinary supernovae of type I. The neutron stars so formed would have a spatial distribution that is far more extended than the mass profile of the massive dark halo. We identify two signatures of these neutron stars: those formed within the past $\sim 10^7$ years are identifiable as high-velocity radio pulsars, some of which should be approaching the disk for the first time, and the energy stored in the crusts or magnetospheres of the somewhat older neutron stars is released as bursts of gamma rays with a nearly isotropic sky distribution.

Neutron stars are commonly considered to form by massive star collapse and death, culminating in a supernova explosion. The stellar envelope is expelled and the core collapses to form a neutron star, detectable as a radio pulsar or as an x-ray binary. Neutron stars should therefore form in the galactic disk. In a somewhat different context, it has been suggested that a component of halo dark matter plausibly consists of dark baryonic matter in the form of compact stellar remnants, which might include brown dwarfs and white dwarfs, or even some neutron stars and black holes, that formed in the early stages of galactic evolution (*1*). It is this hypothesized halo population of compact stellar remnants that provides a source, by white dwarf mergers, of young neutron stars.

It has recently been reported (*2*) that, among a sample of 44 high galactic latitude pulsars, many are moving toward the galactic disk, apparently originating in the halo. This result is surprising at first because fresh neutron star production is traditionally thought to require fresh star formation and supernovae. Inasmuch as neither of these processes is thought to be taking place in the halo, it would then follow that the production of fresh neutron stars in the halo, the simplest interpretation of the observations, is similarly unlikely. In this report, we suggest that high-velocity pulsars are copiously produced in dark populations by white dwarf coalescence, which would

D. Eichler, Department of Physics, Ben Gurion University, Beer Sheva, Israel.
J. Silk, Departments of Astronomy and Physics and Center for Particle Astrophysics, University of California, Berkeley, CA 94720.

not require present-day star formation and would not necessarily result in supernovae (although this may be controversial). This hypothesis requires more massive white dwarfs, in excess of 0.7 solar mass ($M_{\odot}$), than are associated with the initial stellar mass function in the solar neighborhood, for which the mean observed white dwarf mass is 0.6 $M_{\odot}$. These relatively massive white dwarfs are relics of the precursor population of relatively short-lived, massive stars whose remnants are most naturally, we believe, identified with the dark halo.

An alternative mechanism for producing diskward-moving pulsars is the collapse and explosion of runaway OB stars. However, we argue below that the statistics, presently of moderate significance, strain this hypothesis. The existence of one pulsar in the Harrison-Lyne-Anderson survey (*2*) with a transverse velocity of 1000 km s^{-1}, and perhaps another with an even higher velocity that has moved out of its associated supernova remnant (*3*), strain previously discussed mechanisms for generating pulsar velocities, although such mechanisms have admittedly not been quantified. With at least moderate statistical significance, there appears to be a bimodal distribution of pulsar (transverse) velocities in the data of Harrison *et al.* This suggests the need for a distinct mechanism for producing the high-velocity pulsars. Moreover, again at moderate statistical significance, there appears to be a correlation between high transverse velocity and diskward motion: although only about 30% of the pulsars are in the high-velocity peak ($v > 200$ km s^{-1}), three-quarters of the diskward-moving ones are in this peak. More than one-quarter of the high velocity ones, 6 out of 23, are moving toward the disk. In contrast, in the low-velocity peak only 2 of 32 (with known transverse velocities) are diskward-moving. The large fraction of diskward-moving pulsars in the high-velocity group as well as the apparent correlation between direction and speed are difficult to explain with a runaway OB star origin. It motivates a scenario for neutron star formation in which the exceptionally large velocities are natural. Although it is likely that type II supernovae are capable of producing such high velocities (as suggested by the gamma-ray line emission from SN 1987A, which is displaced by 500 km s^{-1}), and that hence some high-velocity neutron stars are attributable to the tail of the normal distribution, one must conclude from the data that the typical pulsar velocity is much lower.

Bias of diskward-moving pulsars to higher speeds is not unnatural, however, if they have a different origin. The pulsars in the survey are at an average distance of about 2.5 kpc and a height above the disk of less than 1 kpc. The high-velocity pulsars are capable of filling a much larger region of space than the low-velocity ones and would do so within the typical spin-down times of the pulsars. This strongly suggests, independent of any theory of their origin, that a significant fraction of galactic neutron stars are in the halo. Moreover, the fact that so many are diskward-moving while being too young to have completed an orbit originating in the disk motivates an alternative interpretation: that they indeed formed in the halo.

A possibly related observation of neutron stars concerns the gamma-ray burst sources originally discovered with early gamma-ray satellites more than a decade ago. The Burst and Transient Source Explorer (BATSE) experiment on board the National Aeronautics and Space Administration Gamma Ray Observatory has found that the distribution on the sky of gamma-ray bursters is nearly isotropic, implying either an origin in the extended halo of the galaxy or a remote origin at cosmological distances, for the simplest classes of models. We choose to identify the gamma-ray bursters as halo neutron stars and show that, with reasonable parameters, the resulting source population would have an isotropy marginally consistent with the first 260 BATSE bursts. A more general implication, however, is that most neutron stars in the cosmos may not be associated with the visible parts of galaxies. For example, the hypothesis that gamma-ray bursts are at cosmological distances need not imply visual identification with galaxies.

Several different hypotheses could be put forth concerning collapsed stars in the halo. One is that the collapsed stars comprise the dark halo matter, as proposed by Silk (*1*). This is the most radical alternative from the point of view of excess light and heavy element pollution, because it requires putting a full 10^{12} $M_{\odot}$ in collapsed stars and requires an initial mass function (IMF) that is far more biased toward the intermediate mass range than our own local solar neighborhood IMF. Another variation postulates merely that most pulsars are in the halo. Because the pulsar lifetimes and production efficiencies could vary from halo to disk for any number of reasons (see below), it is less clear to what extent the IMF is so biased. However, because it could be argued that neither of these variations is likely to differentiate the halo and disk neutron star populations by more than an order of magnitude or so, some bias might still be needed to accommodate the fact that the halo metallicity is 1/100 of the disk metallicity. Finally, the hypothesis that most bursters are in an extended halo works with only a very small fraction of the galactic halo mass, because neutron stars forming in dense clusters in an extended halo may be far more proficient at bursting than those in the disk, as we argue below. The principal constraint is that there are of order 10^3 bursts per year. Because only about 10^{41} ergs of energy is needed per burst, and perhaps 100 to 1000 times that much in crustal relaxation, a rapidly rotating neutron star with, say, 10^{49} ergs in crustal deformation could burst more than 10^5 times as it gradually spins down. Moreover, those neutron stars remaining in the cluster could be continually reactivated via encounters with other stars. Hence, only a very small fraction of the galactic mass need be in halo neutron stars.

We now consider in more detail the hypothesis of white dwarf mergers as a mechanism for generating high-velocity pulsars. We first suggest that the production rate in the halo can fit the observations. Exceptionally large velocities of the nascent neutron stars, it is then argued, are plausible given the circumstances of their origin.

There was certainly some massive star formation in the halo during the collapse stage of the galaxy. The notion that most of the dark matter in the galaxy consists of massive, astrophysical, compact halo objects (MACHOs) has recently been promoted by Silk (*1*). An astrophysically interesting variant of this hypothesis is based on the assumption that the halo material is for some reason deficient in stars in the 0.5- to 1.0-$M_{\odot}$ mass range, namely, that they have a low mass cutoff above ~ 2 $M_{\odot}$. This provides a logical alternative for baryonic dark matter to the more conventional brown dwarf hypothesis, which invokes a high mass cutoff near or below 0.1 $M_{\odot}$. The well-known problem of excessive light production (*4*) can be circumvented if most of the MACHOs formed at high redshift, ($\sim$300), so that starlight is sufficiently redshifted to evade present detection as a diffuse background.

Pollution by a primordial population of stars of intermediate mass is unlikely to be a major problem. For example, extremely metal-poor, intermediate-mass stars do not undergo He shell flashes; hence, dredge-up of carbon is greatly suppressed, at least for the first generation of stars (*5*). Subsequently, in the ejecta from stars of intermediate mass, some He is inevitably synthesized, deuterium is astrated (burnt within stellar interiors), and later stellar generations will produce carbon. Thus, it seems likely that the constraints of heavy element production as well as possible distortions of the cosmic background arising from the stellar radiation (*6*) may require a low rate of production of supernovae in the halo.

However, we believe that even given a traditional stellar IMF with massive as well as intermediate-mass stars, the supernova efficiency could plausibly be suppressed.

Given the high cosmic density and the strong Compton drag at high redshift that would inhibit centrifugal barriers, the high-redshift stars would likely have formed in dense clusters. Hence, stripping of red giant envelopes and mergers in the dense cores may render traditional stellar evolution inapplicable. For sufficiently dense clusters, the merger rate of stars of solar mass by tidal capture at density $\gtrsim 10^7\ M_\odot\ pc^{-3}$ is faster than their main sequence evolution. Mergers are likely to continue until the main sequence evolution keeps pace with the merging. The merging tapers off at some point as a result of core bounce, which depends on the proportion of binaries, so that the extent to which the IMF is modified depends on the cluster parameters and is beyond the scope of this paper. If a dense core can be maintained, red giant envelopes are rapidly stripped and presumably recycled. The qualitative effect of both fusion and stripping is to effectively channel stars into the intermediate mass range.

In any case, we assume that significant numbers of white dwarfs result from population III systems that are now dark and that a significant fraction of them are to be found in binaries. The binary factory effect could make the halo particularly efficient at producing binaries during the evolution of the white dwarf progenitors. The typical end state of close, intermediate-mass binaries is two carbon-oxygen (CO) white dwarfs in an orbit of about 1 to 5 solar radii ($R_\odot$) (7, 8). Reasonable assumptions for the distribution of initial masses and orbital separations suggest that a fraction on the order of 0.2 of the white dwarf pairs would spiral together within 10^{10} years. The distribution of lifetimes τ is roughly uniform in $\ln\tau$, with a low τ cutoff at about 10^8 years, so even steady star formation in the disk does not greatly enhance the present-day production rate of white dwarf mergers.

Moreover, this scenario works best when the progenitors have low metallicity (less than 0.1% of solar), for in this case there is believed to be no envelope expansion before He ignition. A common envelope stage while the white dwarfs are very light ($\sim$0.3 $M_\odot$) He stars, which typically causes the orbit to shrink below 3 $R_\odot$, is thereby avoided. White dwarf mergers could be catalyzed with even higher efficiency inside a cluster by interactions with a third body. We conclude that, per unit mass, the halo can compete favorably with the disk in the present-day production of white dwarf mergers. Hence, even local production, say, within a 3-kpc radius of the sun, could be dominated by the halo. Smecker and Wyse (8) estimate a present-day rate of about 0.2 to 0.5 white dwarf mergers per year in the halo, assuming that it is composed of objects whose precursor IMF is dominated by the 2- to 8-$M_\odot$ mass range. The merger efficiency could be much higher inside globular clusters or related systems. Given a merger rate of 0.3η (η is the normalized merger rate) per year over a halo radius of 100 kpc and a pulsar lifetime (or residence time, whichever is shorter) of 10^8 t_8 years (t_8 signifies time in units of 10^8 years), one estimates a density of about 10^3 ηt_8 high-velocity pulsars within a 3-kpc radius of the sun. This is easily compatible with the observations and the estimated merger rate, even if the binary factory effect is neglected. Thus, the halo mass fraction needed for binary white dwarf progenitors in the IMF can be quite small.

We now suggest that pulsars arising from white dwarf mergers could have, on average, higher velocities than those generated in type II supernovae. First, infall from high galactic latitudes could account for additional velocities of up to several hundred kilometers per second, depending on the site of origin. In addition, it stands to reason that, having a different origin, such neutron stars would have a different distribution of kick velocities than those neutron stars of conventional origin. Given that the total mass of the CO white dwarfs exceeds 1.4 $M_\odot$, the final stages of nuclear burning and eventual electron capture are mediated by the gradual loss of rotational support of the merger. If the white dwarf masses are somewhat different, the less massive object is tidally disrupted and accretes onto the companion. However, unless the accretion is slow, this does not give rise to a typical type Ia supernova but rather leads to off-center C ignition and hence to a less conspicuous collapse (9). Moreover, the presence of strong magnetic fields and crystalline chunks of degenerate matter could break even the axial symmetry of the ignition and cause modest, asymmetric mass ejection, which could provide a velocity kick. A demonstration of this effect, unfortunately, would require prohibitively detailed three-dimensional hydrodynamical calculations. Further theoretical uncertainties are discussed by Canal, Isern, and Labay (10), who contend that thermonuclear runaway in collapsing CO white dwarfs is still an open question.

A second possible mechanism for providing a velocity kick is the gravitational ejection of fragments during the collapse. Electron capture in the equatorial plane of the merger allows collapse along the rotational axis that is much faster than angular momentum loss, giving rise to a highly flattened system that is assumed to fragment. The lightest fragment, of mass m_ℓ, is probably ejected with a modest fraction ($\sim$1/3) of the orbital velocity, which is of order 10^9 cm s^{-1}, and the remaining fragments, having total mass m_t, then recoil with a velocity of order 3×10^8 (m_ℓ/m_t) cm s^{-1}. Gravitational radiation or tidal disruption causes the two heaviest fragments to merge into a high-velocity neutron star, whose velocity, though perhaps broadly distributed according to the fragmentation spectrum, could easily be $\sim 10^8$ cm s^{-1} if the tendency is to fragment into several large pieces. If the recoil fails, as occasionally may happen, any "planets" (11) that may have formed (for example, during the phase of envelope expulsion) should survive in orbit around the neutron star, suggesting a possible scenario that merits further investigation.

There may be alternatives to producing high-velocity pulsars, such as release from tight orbits or unusually strong kicks from supernovae. There may also be alternatives to producing pulsars out of the plane, such as core collapse of runaway B stars. But B stars would have had to move of order 1 kpc from the plane before producing the pulsars, implying that they are only a fraction of the total number of runaways, and the large fraction of high-velocity pulsars that are diskward-moving strains this alternative hypothesis. Under the present hypothesis, the halo can produce as many as or more high-velocity pulsars than the disk because it contains more close, intermediate-mass binaries with separation just under 3 $R_\odot$. Yet it produces much less light because of its lack of both 0.5- to 1-$M_\odot$ stars and new star formation. Observationally, the halo is required to product far fewer supernovae and low-mass x-ray binaries (LMXBs). If most of the neutron stars are produced in the halo by gradual merging of white dwarfs, so that the collapses are "quiet" and the neutron star velocities large, a low yield for bright supernovae and LMXBs can be understood. LMXB formation can, of course, be further suppressed by the lack of low-mass stars. Formation of LMXBs consisting of white dwarf companions is probably not suppressed; however, such small-period systems, driven by gravitational radiation, would be extremely short-lived.

A potential problem may be that conditions for setting up white dwarf mergers could produce, in parallel, a high yield of type Ia supernovae. Apart from the many uncertainties in the pulsar formation rate in the halo required by our hypothesis, the ratio of white dwarf mergers to type Ia supernovae could vary from disk to halo for any number of reasons. For example, if the halo objects are in dense clusters, encounters with a third body could influence this ratio; or else the white dwarf binaries that are otherwise left in orbits too wide for decay by gravitational radiation could be perturbed by third-body encounters into rapidly decaying orbits.

However, there is a more fundamental

issue to do with the nature of type I supernovae. Although type Ia supernovae are generally considered to have originated as exploding white dwarfs (*12*), the precursor state remains uncertain. The hypothesis of double white dwarf mergers (*13, 14*) requires a frequency of nearby close white dwarf binary pairs that appears to be in excess of observational limits (*15–17*). Moreover, such a precursor model is characteristic of an old population and would be in conflict with the higher frequency of type Ia supernovae per unit infrared luminosity observed in late-type relative to early-type galaxies (*18*). The outcome of a double degenerate merger could plausibly result in an optically subluminous event relative to the standard Ia supernova. If type Ia supernovae indeed depend on accretion from a nondegenerate object, it is not surprising that their present rate in halos is very small. There remains the question of whether type Ia supernovae would have polluted the halo with heavy elements before the gas settled into a disk. The yields are sufficiently uncertain that we regard this matter as unresolved. We conclude that the status of type Ia supernova precursors is too uncertain at present to permit us to make statements with any confidence about the observable signature of a white dwarf merger.

These problems arise only if the neutron stars and white dwarf binaries associated with the mergers comprise most of the galactic mass. The enhanced efficiency with which dense clusters could yield active neutron stars allows one to hypothesize a much smaller mass for the population of the neutron star precursors.

Deeper pulsar surveys out of the plane of the disk would test the claims made here, which are thus far based on only modest statistics. An ambitious observational program could conceivably establish the angular distribution of faint pulsars. Another possible observational consequence of this scenario is the gravitational radiation that would be generated by the merging of two protoneutron star fragments during the final stages of the merger. Although less luminous than the "standard" merger of two $1.5\text{-}M_{\odot}$ neutron stars, the association of such mergers with high-velocity pulsars would suggest a rate that could easily be higher than one per galaxy per 100 years, much higher than even liberal estimates for the rates of neutron star mergers (*19–21*). If such an event were to take place in our own galactic halo, the gravitational signal would be all the more conspicuous, unless the protoneutron star were almost perfectly axisymmetric in its final stages of collapse.

Neutrino emission in the final stages of collapse may also provide a possible detection mechanism, if the output and distance are comparable to those of SN1987A, but, because the collapse is bottlenecked by the angular momentum shedding, it is hard to predict the neutrino detectability with confidence. The typical distance of a bursting neutron star is about twice that of the Large Magellanic Cloud (LMC), where SN1987A gave rise to a short burst of about ten neutrinos detected in the Kamiokande and Irvine-Michigan-Brookhaven underground experiments. The formation events that produce the neutron stars, although deficient in optical radiation, could possibly produce a characteristic neutrino signature similar to that observed from SN1987A, but weaker by a factor of at least a few.

Gravitational microlensing (*22*) in our own halo may eventually provide a more general test of the MACHO hypothesis. This microlensing test for MACHOs works marginally over several years if they fully comprise the galactic dark matter. But it could fail if they are concentrated into dense aggregates that avoid the lines of sight in the search (or if the MACHOs are far fewer in number than suggested by the dynamical maximum). However, the possibility of dense aggregates suggests a complementary dark matter diagnostic, which could perhaps detect stellar aggregates of total mass m down to globular cluster masses. Out-of-plane pulsars could be mostly free of their parent clusters, if they undergo a kick at birth, but could by chance lie near enough to another, with probability of order $(m/M_{\rm gal})^{1/2}$, where $M_{\rm gal}$ is the mass of the galaxy. Pulsar timing, which has already measured the galactic acceleration of at least one pulsar, could in principle use a large number of pulsars found in the halo to find such aggregates. Implementation of this idea presumably lies in the distant future, because, if m is small, a large number of pulsars are probably needed. Pulsars that remain within their cluster of origin, however, might be quickly identified as such by their local acceleration. The existence of even a single pulsar with a negative period derivative that could not be identified with a visible globular cluster would be evidence for a massive local concentration of dark matter.

The first BATSE results have recently been reported (*23*). The unexpected results include isotropy of gamma-ray bursts to at least 10% accuracy, $\langle \cos\theta \rangle \sim 0 \pm 0.035$ after 260 bursts, and a fluence function that is inconsistent with a homogeneous distribution. This has led many to conclude that the bursts are at cosmological distances, as suggested several years ago (*19, 24–26*). On the other hand, the cyclotron absorption features (*27*), the power law spectra that extend out to 100 MeV, and the absence of galaxies at the positions of well-located bursts are not simple to explain within the cosmological hypothesis, so it is reasonable to consider whether the bursts could be at halo-like distances, say, of order 100 kpc. Such distances would be more or less consistent with the identification of the 5 March 1979 burster with supernova remnant N49 in the LMC. Starquake models (*28*), in which the gamma rays result from a magnetospheric disturbance, may be one way to account for these energetics, since 10^{44} ergs are in principle available in a crustal relaxation event, but the efficiency with which this energy is transmitted to the magnetosphere (perhaps via an emergent shock wave), would need to be at least 10^{-3} or so. In either case, there are grounds for suspecting that bursts do not come from the visible parts of galaxies. For example, well-localized bursts, which are necessarily bright ones to have been detected simultaneously by three or more spacecraft, have not been associated with any galaxy. This is explained naturally if the bursters are in extended halos or are of intergalactic origin.

We now consider whether the present limits on anisotropy could permit the bursters to be in an extended halo of our own galaxy. If the bursters form in systems comparable in mass and density to globular clusters or ultradense dwarf galaxies that formed at high redshift z, their distribution should be far more extended than the massive halo, which, if baryonic, may be associated with dissipative infall of gas. The high velocities of the halo neutron stars discussed here would, moreover, cause their distribution to be much more extended than the distribution of their formation sites. The absence of coincidence of any gamma-ray burst sources with pulsars had led to the view that the burst stage of a neutron star must be longer than the pulsar stage. Perhaps this is enforced by the pair multiplication mechanism usually associated with pulsar magnetospheres preventing efficient gamma-ray generation (*28*). The spin-down time of the fast pulsars in the survey of Harrison *et al.* (*2*) ranges up to 10^8 years. Thus, lifetimes for the burst stage in excess of 10^8 years, and hence distances in excess of 50 kpc, are reasonable. Distances of order 1 Mpc, problematic because of a lack of anisotropy in the direction of M31, may be suppressed by a decline in the burst rate with time or by a detection threshold. A more detailed analysis is in order but beyond the scope of this discussion. Burst energies of up to 10^{41} ergs per burst are assumed here, rendering the infamous 5 March 1979 burst exceptionally large but not pathologically so, and the subsequent bursts typical. This would permit detection out to ~200 to 300 kpc. The total release of energy could be as high as 10^{44} ergs, but, if the energy source is crustal deformation energy in, say, dead millisecond pulsars, then as many as 10^5 bursts could still be generated per burster. In principle, then, only a small amount of mass need be present in the halo neutron stars in order for them to account for the burst rate.

A tentative model for bursters in an extended halo would be a distribution of neutron stars that is approximately homogeneous out to some core radius R_c and that tends to an R^{-2} density distribution at the largest radii. The ln$N$-ln$S$ plots of the BATSE bursts are consistent with an inner homogeneous core, with a slope $d\ln N/d\ln S \approx 0.8$ at large distances (S is the fluence of bursts in ergs per square centimeter and N is the number of bursts with fluence $\geq S$). A nearly equivalent representation, preferable if the detection threshold is variable, is in terms of the ratio of the volume V of a sphere extending to the burster to the volume of a sphere extending to the maximum distance at which a burst would be detectable, V_{max}. We illustrate this result in Fig. 1, where the V/V_{max} distribution of BATSE bursters is fit for a burst differential luminosity function that is proportional to L^{-2}, with a range in burst luminosity L of a decade and in a halo in which the burster distribution has core radius R_c = 40 kpc. A more detailed grid of halo models will be presented elsewhere (*29*). The results are sensitive primarily to R_c; a much larger value would result in the M31 halo being detectable in the gamma-ray burst distribution, where excessive anisotropy results if R_c < 30 kpc. For this choice of parameters, we calculate the expected anisotropy to be $<\cos\theta> = +0.05$, which is within 1 SD of the observed anisotropy for the first 300 BATSE bursts. This will become a prediction at the 2 SD level after the number of bursts accumulates by another factor of 3. Some freedom still remains in choosing the maximum radius and luminosity function for the bursts, so the quoted statistical confidence retains a small amount of flexibility.

The existence of high-velocity pulsars in the halo is suggested merely by the observational data; the possibility of their being gamma-ray burster progenitors is, to a large degree, independent of the theoretical model for their formation. Moreover, the representation of the neutron star populations among the gamma-ray burst sources may be origin-dependent. Neutron stars formed by white dwarf mergers, for example, may have more energy stored in their crusts than those formed in supernovae. Hence, the disk, even if it is an occasional burst site, need not contaminate the isotropy of the burst distribution.

Finally, we consider the possibility that the bursts have a cosmological origin but nevertheless are associated with neutron stars. If the bursters are distributed as luminous stars, then bright bursts, presumably the ones that are close by, should in principle be identifiable with the visible parts of galaxies. If the typical

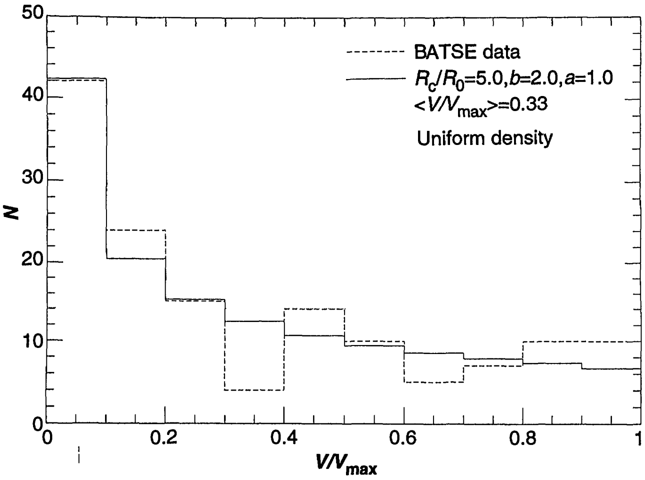

Fig. 1. The V/V_{max} distribution for gamma-ray burst sources compared with predictions of the halo model for an adopted halo core radius of gamma-ray burst sources equal to five times the solar galactocentric distance. Here V is the volume contained by a sphere extending to the burst and V_{max} is the volume of a sphere extending to the maximum distance at which the burst would be detectable; for a uniform distribution, V/V_{max} = 0.5. The model plotted assumes a burst source luminosity function proportional to L^{-2} and a range in luminosity of a decade but is insensitive to these assumptions (*29*). The BATSE data are taken from (*23*).

redshift for faint BATSE bursts is at modest redshift $z \leq 1$, as determined by the V/V_{max} distribution (30), then at least several bursts per year should occur well within 1 Gpc. Angular resolution of 3×10^{-5} rad, which should be attainable in principle with multi-spacecraft triangulation, involving the spacecraft Ulysses, Pioneer Venus Orbiter, and Gamma Ray Observatory, would provide resolution of better than 30 kpc. At this angular resolution, the problem of chance galaxies lying near the line of sight should not be prohibitive. For bright bursts, with fluences of 10^{-5} erg cm^{-2}, some models of cosmological bursts would be strained if the bursts are assumed to occur at distances exceeding 1 Gpc, because they would involve total energies in excess of 10^{51} ergs. Clearly, a sample large enough to include the brightest bursts with good time structure could provide a statistically viable sample of strong candidates such that lack of correlation with host galaxies would be significant. Future gamma-ray burst detectors, such as coded mask detectors, may further improve the angular resolution. Thus, a test of whether most bursters lie within the visible parts of galaxies, already ruled out if the bursters are local, is possible even if they are at cosmological distances.

If bursters are produced by white dwarf coalescence, then the final stages of this process, as the object becomes a neutron star, would resemble other cosmological scenarios for producing the bursts themselves, such as accretion-induced collapse and neutron star coalescence, and could be considered in such a class of models. Such scenarios often invoke very strong magnetic fields (*24, 31*); in particular, the magnetic flare model (*31*) would store of order 10^{50} ergs of energy in the field. A possible difference between neutron star merging and neutron star formation by white dwarf merging, apart from a factor of several in total available energy, would be that the neutron star, which may have formed with very large fields frozen into its crust, is available later on for weaker repetitions (*24*) as the magnetic field further simplifies. However, an estimate of the time scale for the repetitions requires more detailed study.

We have proposed the unconventional but simple hypothesis that most neutron stars form outside the visible parts of galaxies. We have suggested that ultradense clusters, predominantly comprising compact stellar remnants that formed at high redshift, would be subluminous repositories of ongoing white dwarf mergers, which in turn would provide the dominant source of pulsars or gamma-ray bursters, or both, in the universe. High-velocity pulsars and gamma-ray bursters may thus be among the first detected manifestations of massive, compact objects in the halo. In its most extreme form, the hypothesis invokes collapsed stars as the dark halo matter itself, and several of the standard objections to this hypothesis, such as overproduction of supernovae, were argued to be surmountable. However, accounting for gamma-ray bursts or diskward-moving pulsars, or both, requires only 10^7 to 10^9 neutron stars in the halo. The hypothesis of halo or extragalactic neutron stars should in any case be considered in the spirit of devil's advocacy, as it does not appear to be impossible. Several observations to be performed over the next decade or so could conceivably verify or falsify our hypothesis.

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Benzene Forms Hydrogen Bonds with Water

Sakae Suzuki, Peter G. Green, Roger E. Bumgarner, Siddharth Dasgupta, William A. Goddard III, Geoffrey A. Blake*

Fully rotationally resolved spectra of three isotopic species of 1:1 clusters of benzene with water (H_2O, D_2O, and HDO) were fit to yield moments of inertia that demonstrate unambiguously that water is positioned above the benzene plane in nearly free internal rotation with both hydrogen atoms pointing toward the π cloud. Ab initio calculations (MP2 level of electron correlation and 6-31G basis set with basis set superposition error corrections) predict a binding energy $D_e \gtrsim 1.78$ kilocalories per mole. In both the experimental and theoretical structures, water is situated nearly 1 angstrom within the van der Waals contacts of the monomers, a clear manifestation of hydrogen bond formation in this simple model of aqueous–π electron interactions.**

We report the ground-state microwave spectra of jet-cooled C_6H_6-H_2O along with an ab initio calculation of the intermolecular potential energy surface (IPS). Our goals are, first, to establish experimentally the structure and ground-state energy levels of the complex free of external perturbations, such as many-body solvent interactions and macromolecular structures and, second, to gain a global theoretical understanding of the IPS in order to guide future searches and to provide estimates of the binding energy and anisotropy of this prototypical model of aromatic-hydrophilic interactions. Compared to other methods, fully rotationally resolved cluster spectra of the type presented below are perhaps the most direct approach to an understanding of the structural implications and energetics of weak intermolecular forces at the two-body level.

It has been speculated for several years that aromatic rings can act as hydrogen-bond acceptors (*1, 2*). Recently, compelling but indirect evidence for the hydrogen-bonding character of aromatic rings to water and other biologically significant materials has been found in a number of experiments, ranging from low-resolution ultraviolet (UV) and infrared (IR) spectroscopy of molecular clusters in supersonic jets (*3*) and in matrices (*4*) to x-ray crystallographic structures of a variety of proteins (*2*) as well as specifically designed synthetic materials (*5*). Although the hydrogen positions were not directly located in these studies, they provided strong support for an interaction of hydrogen bond donors with the high electron density of the aromatic π cloud. Aromatic-polar interactions may also play significant roles in many natural chemical systems and reactions, ranging from the tertiary structure (*6*) and function (*7*) of biopolymers to reactions on atmospheric aerosols (*8*). They may also provide a variety of molecular recognition motifs (*9*).

That aromatic rings act as hydrogen bond acceptors illustrates dramatically the need for a molecular description of phenomena such as the hydrophobic effect so familiar at macroscopic scales. Aromatic hydrogen bonds, like essentially all weak interactions, are not well characterized at the molecular level, and much of our understanding is based on chemical intuition and theories in which the practical limitations of current computing power forces us to make what are often drastic assumptions and simplifications with unknown consequences.

An arbitrary structure of the benzene-water complex that shows the intermolecular coordinate system used is presented in Fig. 1. Weak intermolecular forces allow a number of large amplitude motions to occur in clusters such as C_6H_6-H_2O and necessitates the use of permutation-inversion (PI) theory [(*3*) and references therein], in which all "feasible" motions are considered, in order to understand the vibration-rotation-tunneling (VRT) spectra of these clusters. Such VRT spectra should allow intermolecular forces in weakly bound clusters to be probed at unprecedented levels of detail (*10, 11*). Here, there are two potentially feasible motions: (i) an internal rotation of the water relative to the benzene in a sixfold potential; and (ii) assuming the monomer C_2 and C_6 axes are not aligned, an interchange of the H_2O protons in a double minimum potential. Several studies, such as the matrix isolation work of Engdahl and Nelander (*4*) and especially the resonance ionization experiments through the S_1 state of benzene by Gotch and Zwier (*3*), have unambiguously demonstrated that the internal rotation is nearly free and that, on a vibrationally averaged basis, the hydrogens are equivalent.

A detailed experimental investigation of these large amplitude motions, and by extension the IPS, requires the measurement of all of the VRT modes of C_6H_6-H_2O, which occur in the far-IR (FIR) region of the spectrum. We have used the Caltech tunable FIR laser spectrometer to measure the VRT states for a range of water-containing complexes such as CO-H_2O and NH_3-H_2O (*12, 13*). However, high-resolution microwave spectra, which often provide good structural estimates and form a useful starting point for FIR work, do not exist for the C_6H_6-H_2O complex.

We have previously described our microwave version of the Caltech cluster spec-

S. Suzuki, Division of Chemistry and Chemical Engineering, 164-30, California Institute of Technology, Pasadena, CA 91125.
P. G. Green, R. E. Bumgarner, G. A. Blake, Division of Geological and Planetary Sciences, 170-25, California Institute of Technology, Pasadena, CA 91125.
S. Dasgupta and W. A. Goddard III, Materials and Molecular Simulation Center, Beckman Institute, 139-74, California Institute of Technology, Pasadena, CA 91125.

*To whom correspondence should be addressed.