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DEGENERATE DWARF BINARIES AS PROMISING, DETECTABLE SOURCES OF GRAVITATIONAL RADIATION[1,2]

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ABSTRACT

Recent theoretical work suggests the presence in our Galaxy of a large population of degenerate dwarf binaries (DDBs) which have orbital separations small enough that the components are brought into contact by gravitational radiation emission on time scales from 10^5 to 10^{10} yr. In the last *e*-folding time prior to merger, those systems closest to Earth will individually produce periodic gravitational wave (GW) amplitudes of the order of $h \approx 1 \times 10^{-21}$ in the frequency range 10–100 mHz. A recent preliminary design for a space-based laser interferometer indicates that sources of this kind, are potentially detectable. We discuss the characteristics likely to be seen in such an antenna from degenerate dwarf binaries, assuming theoretical birth rates. At low frequencies the signal is dominated by superposition of unresolved binaries which produce an effective continuum. At high frequencies, individual binaries should be resolvable above the continuum.

In addition to the periodic signal emitted during orbital decay, DDBs may also emit burst signals of several types. Depending on system parameters, the less massive component may transfer mass on a dynamic time scale once Roche lobe contact occurs. It is expected that the lighter component will be transformed into a massive disk or giant envelope about the more massive component, with a concomitant rapid diminution of the periodic GW signal. If the total mass of the system exceeds the Chandrasekhar mass, the subsequent process of merging may lead to collapse of the primary to a neutron star, especially if the heavier dwarf is composed of oxygen and neon, or to a star disrupting explosion with a resultant Type I supernova optical display, if the dwarfs are composed of carbon and oxygen. In either case, the high spin rate that the more massive component may be expected to acquire during the accretion process introduces nonsphericities. Hence, GW emission would occur during either implosion or explosion of the dwarf. If a neutron star forms, rotation rates comparable with the 1.5 ms pulsar, PSR 1937+21, might occur, producing a near maximum strength gravity wave signal.

Subject headings: gravitation — radiation mechanisms — stars: binaries — stars: evolution — stars: neutron

I. INTRODUCTION

Thus far, the most convincing evidence for the emission of gravitational waves (GW) is the fact that the observed rate of decrease of the orbital period of the binary containing PSR 1913+16 is in excellent agreement with the rate predicted by general relativity (e.g., Taylor and Weisberg 1982). With an orbital period of about 8 hr and a total binary mass of about 2.8 $M_\odot$, this system, if it is at a distance of 6 kpc, should produce at Earth a GW energy flux F_{GW} of about 10^{-15} ergs cm^{-2} s^{-1} and a GW amplitude $h \approx 10^{-23}$ at a frequency $f_{GW} \sim 0.07$ mHz. Unfortunately, direct detection of GW from a relatively secure source such as PSR 1913+16 is far beyond the capability of present instruments and of terrestrial detectors under design for the next decade.

Of known periodic sources, those which are expected to produce the largest strains at Earth are the classical close optical W UMa binaries of which i Boo and μ Sco are the most fully studied local representatives. The system i Boo has the characteristics: period $P \approx 6^h.47$, total binary mass $M \approx 1.5\ M_\odot$, orbital separation $A \approx 2\ R_\odot$, and amplitude $h \approx 1.5 \times 10^{-20}$, at the frequency $f_{GW} \approx 0.09$ mHz. GW radiation from these binaries was first considered by Mironovskii (1966); see also Douglass and Braginsky 1979. The latter authors have also considered GWs from cataclysmic variable systems. Although i Boo and μ Sco produce amplitudes on the order of $h \approx 10^{-20}$, their emissions are at such low frequencies (0.02 mHz for μ Sco and 0.09 mHz for i Boo) that they similarly cannot be detected by terrestrially confined devices of conventional design. Seismic motion severely limits the use of terrestrial laser interferometers at frequencies below 100 Hz (Drever and Weiss 1986).

To date, most of the effort that has gone into designing GW detectors (bars and laser interferometers) has focused on the potential detection of GW radiation thought to be emitted during either (1) the collapse to a neutron star or black hole of the core of a massive star accompanying a type II supernova (SN II) explosion or (2) by the final stages in the coalescence of a binary neutron star or binary black hole system. In the case of supernova core collapse this emission should be a broad-band, impulsive signal centered

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in frequency at near 1 kHz. Unfortunately, although the frequency of occurrence of SNe II in galaxies is roughly known (~ 1 per 20–100 yr per galaxy like our own), the strength of the GW signal emitted during core bounce is a strong function of the nonsphericity of the core. This nonsphericity is presumably related to the angular momentum distribution in the immediate collapse precursor and there are scant observational or theoretical arguments which can provide plausible estimates of the precollapse core angular momentum. The maximum amplitude that could be expected from a Type II event occurring at the distance of the Virgo cluster (20 Mpc), where an event rate of one or more per year is likely, is $h \approx 10^{-21}$ at a frequency of ~ 1 kHz. The recent supernova, SN 1987A, if it formed a neutron star, could have produced a maximum burst amplitude of $h \approx 0.7 \times 10^{-18}$ (Bahcall, Dar, and Piran 1987). These are very optimistic numbers; in fact, both these estimates of maximum possible amplitude may be a factor of 30 lower if the collapse remains axisymmetric. Many collapses may produce actual amplitudes that are orders of magnitude smaller. Currently operating detectors in this frequency range can respond to signals only in excess of $h \approx 10^{-18}$. Detectors envisioned to be available by the mid-1990's may reach sensitivities to bursts of order $h \approx 10^{-22}$ (Drever and Weiss 1986). Detector sensitivity improves for nearly periodic sources like coalescing binaries, since integration time, τ, increases sensitivity at the rate $\tau^{1/2}$. A neutron star binary with component masses of 1.4 $M_\odot$, at a distance of 100 Mpc, produces a signal amplitude of 2×10^{-23} when $f_{GW} = 100$ Hz; the effective amplitude after integrating to improve by $\tau^{1/2}$ is 3×10^{-22}. In proposed terrestrial interferometers (Drever and Weiss 1986) this corresponds to a maximum signal to noise ratio of 30 (Schutz 1986). Here the complication is the event rate. It has been estimated (Clark, van den Heuvel, and Sutantyo 1979) that there are about three such events per year within 100 Mpc, but this figure is considerably uncertain. If detectors are restricted to frequencies $f_{GW} \gtrsim 100$ Hz, we can only see these systems as transient events lasting a few seconds.

In summary, typical optical binaries produce periodic GW signals of predictable and sizable strengths, but at low frequencies that make detection impossible with present schemes. Stellar core collapse events produce burst signals at frequencies for which terrestrial devices have been designed, but do so at strengths that are at present not well known. Coalescing neutron star or black hole binaries should be detectable in the next decade, but the event rate is uncertain.

Another class of objects—pairs of degenerate dwarfs in close binaries—have been discussed as potentially detectable sources in the 0.01–100 mHz range (e.g., Clark 1979; Tutukov and Yungelson 1979; Massevitch, Tutukov, and Yungelson 1981). Until recently, however, there has been little basis for estimates of the occurrence frequency or of the space density of such objects. The possibility of detecting GWs from them via a space-based interferometer in solar orbit (Faller and Bender 1984; Faller *et al.* 1984; Hils *et al.* 1987) makes it worthwhile to explore the implications for GW astronomy which new theoretical estimates of occurrence frequency make possible. In contrast to cataclysmic variables and W UMa stars, precontact degenerate dwarf binary (DDB) orbits evolve very predictably, due to just GW radiation reaction. Provided with an overall birthrate, the orbital evolution determines a fairly unambiguous distribution for the number of binaries as a function of f_{GW}. In addition, the compactness of both components allows DDB systems to reach $f_{GW} \approx 100$ mHz before coalescence.

Iben and Tutukov (1984*a*, *b*; 1986) predict that close pairs of degenerate white dwarfs should be the end product of the thermonuclear evolution of $\sim 20\%$ of all binary systems (see also Webbink 1984 and Paczyński 1985). The most common pairs are expected to be composed predominantly of helium (He dwarfs), forming at a frequency in the Galaxy of roughly $\nu_{HeHe} \approx 0.15$ yr^{-1}. Pairs consisting of a helium degenerate dwarf and a degenerate dwarf composed primarily of carbon and oxygen (a CO dwarf) should occur at the rate $\nu_{COHe} \approx 0.02$ yr^{-1}, while pairs of two CO dwarfs should occur at essentially the same rate ($\nu_{COCO} \approx 0.02$ yr^{-1}). As we show in § II, the estimates of formation frequency imply the existence in our Galaxy of some 10^4 or so binary systems consisting of two very close white dwarfs emitting GW at large rates in the 10–100 mHz range.

Eventually, when the orbital separation of the binary becomes small enough, the secondary (less massive component) will contact its Roche lobe and mass transfer will begin (Faulkner 1971; Vila 1971; Tutukov and Yungelson 1979; Webbink 1984; Cameron and Iben 1986). In many systems, the mass transfer may be sufficiently rapid that the secondary is transformed into a thick disk or giant envelope about the primary (Tutukov and Yungelson 1979; however, see Hachisu, Eriguchi, and Nomoto 1986). Most pairs have a total mass which is less than the Chandrasekhar mass (1.4 $M_\odot$) and the subsequent growth of the central white dwarf by accretion from the thick disk or giant envelope will not result in a SN I explosion. The net result may be a single, rapidly spinning white dwarf. However, perhaps half of the double CO degenerate dwarf pairs ($\nu_{SNI} \approx 0.01$ yr^{-1}) are massive enough (Iben and Tutukov 1984*a*, *b*; 1985) that accretion may ultimately result in an explosion. In rarer instances, accretion on ONe white dwarfs to the Chandrasekhar mass may lead to collapse to a neutron star (Nomoto 1984). The rapid spin rate produced in the accreting primary is sufficient to lead to a millisecond pulsar, like PSR 1937+21, following collapse.

For some 10^2–10^4 yr prior to Roche lobe contact, the emission of narrow band GWs at frequencies in the approximate range $f_{GW} = 10$–100 mHz will occur at high rates (typically of order $L_{GW} \approx 10^{37}$ ergs s^{-1}). Once Roche lobe contact occurs, the GW signal becomes much more difficult to predict. Since the total rate with which systems should be merging in our Galaxy is of the order of one every 5 yr ($\nu_{HeHe} + \nu_{COHe} + \nu_{COCO}$), it would be interesting to identify signals from binaries with the shortest orbital periods ($f_{GW} \approx 100$ mHz). In § III we point out that these should stand out well above the unresolved continuum, which dominates at lower frequencies, and that within a year the orbital decay ($\dot{P}$) would be measurable.

In § II we briefly discuss several candidate DDBs and related systems and the observational difficulties in establishing the presence of a population of DDBs. We also relate several aspects, relevant to the calculations in this paper, from the theory of binary star evolution that predicts close DDB formation. Section III analyzes in detail the detectability of these hypothetical sources, assuming that the characteristics of currently envisioned space-based laser interferometers can be achieved. The acceptance band of these interferometers, roughly 0.1–100 mHz, spans nearly the entire range of interesting DDB periods, particularly the high-frequency range 10–100 mHz. The proposal sensitivity is sufficient that large numbers of individual galactic sources will be resolvable above the continuum at high frequencies ($f_{GW} \gtrsim 1$ mHz). At lower frequencies ($f_{GW} \lesssim 1$ mHz), sources overlap in frequency space, giving rise to an effective continuum. The limit here is due to the effective bandwidth of the instrument set by the source frequency and the limited spacecraft lifetime ($\gtrsim 3$ yr).

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II. THE ARGUMENT FOR LARGE NUMBERS OF CLOSE DEGENERATE DWARF BINARIES

Recent theoretical estimates suggest that a large fraction of binary systems which are initially composed of intermediate-mass main-sequence stars should evolve into close DDBs. The production of DDBs naturally breaks into several distinct classes delineated by the compositions of the component dwarfs (and hence roughly by their masses). In order of decreasing likelihood of occurrence, these are helium + helium pairs (He + He), carbon-oxygen + helium pairs (CO + He), and carbon-oxygen + carbon-oxygen (CO + CO) systems. In addition, there is expected a less frequently formed class of DDBs, those containing more massive oxygen-neon-magnesium (ONe) primaries.

Some of the degenerate CO dwarf systems may evolve into normal SNe I (Tutukov and Yungelson 1979; Webbink 1979; Iben and Tutukov 1984*a*, *b*; Webbink 1984; Paczyński 1985; Iben 1986), whereas some of the systems containing ONe degenerate dwarfs may evolve into Type I peculiar SNe (see Cameron and Iben 1986 and Iben 1986). If these evolutionary routes for the production of SNeI are correct, then one may use the observed SN I formation rate to estimate directly the occurrence frequency of close binaries containing massive white dwarfs in the last *e*-folding time prior to merger and explosion. These sources are expected to be among the most potent among the DDBs as periodic GW sources.

In addition, some of those DDBs with ONe primaries may give rise to collapse and neutron star formation following Roche lobe contact and mass transfer. As accretion pushes the primary mass toward the Chandrasekhar mass, collapse initiates before significant burning of oxygen and neon occurs. Once nuclear burning starts, the energy released is insufficient to halt the collapse (Nomoto 1984) and a neutron star forms, followed by an underluminous supernova explosion (Mayle and Wilson 1987). Such systems if sufficiently spun up by accretion may produce very strong impulsive GW signals and a remnant millisecond pulsar. If we take an initial ONe primary to have a mass of 1.1 $M_\odot$, its radius is $R \approx 6.9 \times 10^{-3}\ R_\odot$ and its moment of inertia is $I \approx 7.7 \times 10^{49}$ g cm^2. If the primary accretes material from a Keplerian disk, only $\Delta M \approx 0.02\ M_\odot$ is required to deposit an angular momentum of $J \approx 10^{49}$ g cm^2 s^{-1}. This modest amount of accreted material would spin the dwarf up to a period of $P \approx 45$ s. This value of angular momentum is sufficient to yield a millisecond rotation period in the neutron star following collapse and is the near optimal value required for an efficient GW burst during neutron star formation.

As an illustration, we sketch the evolutionary routes whereby CO + CO presupernova systems are thought to be formed; further details may be found in Iben and Tutukov (1984*a*, *b*; 1985; 1987) and in Iben (1986, 1987). In systems with intermediate-mass components of initial main-sequence mass in the range $\sim$5–9 $M_\odot$ and with separations of order $\sim$70–500 $R_\odot$, the initially more massive (or primary) star will overflow its Roche lobe after exhausting hydrogen at its center but before igniting helium there. Mass transfer out of the primary is extremely rapid during this phase, with $\dot{M}_1 \approx 10^{-3}\ M_\odot$ yr^{-1}. The more compact main-sequence secondary cannot accrete at this rate, but swells to fill its own Roche lobe, leading to the formation of a common envelope (e.g., Sparks and Stecher 1974; Paczyński 1976; Meyer and Meyer-Hofmeister 1979; Bodenheimer and Taam 1984). The helium remnant of the primary has a mass in the range $\sim$0.7–1 $M_\odot$ and hence the common envelope contains considerable mass: $\sim$4–6 $M_\odot$. All calculations to date of what occurs during this common envelope stage can at best be characterized as rudimentary. The problem is inherently difficult, requiring three-dimensional modeling and a wealth of physical detail. Nonetheless, it is presumed that drag forces and impact by the envelope gas on the double core components leads to stirring and shock heating of the gas. It is expected that this heating will be sufficient to drive off the common envelope in a shell resembling a planetary nebula. The energy required to drive off the envelope must come from the release of gravitational binding energy contained in the binary orbit as the drag of the envelope causes the stellar components to spiral toward each other. On simple energetic grounds, the energy required to lift off the massive envelope will draw the helium core and primordial secondary to within $A \approx$ 10–70 $R_\odot$. Helium burning in the primary remnant will convert this star to a degenerate CO dwarf of mass 0.7–1.0 $M_\odot$ in a few times 10^5 yr.

The next phase begins as the primordial secondary evolves off the main sequence. Roche lobe overflow ensues, with the formation of a second common envelope. The evolution of the core of the secondary is similarly arrested, leaving a helium core of mass comparable to the mass of the CO dwarf primary (0.7–1.0 $M_\odot$). The process of driving off the second common envelope reduces the separation of the stellar remnants to $A \approx$ 0.2–1.4 $R_\odot$. Subsequent helium burning converts the secondary into a CO dwarf.

The only remaining evolutionary driving force at this point is the loss of orbital angular momentum due to GW emission. For an orbit of separation A, the period is

$$P = \left(\frac{4\pi^2 A^3}{GM}\right)^{1/2} = 103\ \mathrm{s}\left(\frac{M}{0.6}\right)^{-1/2}\left(\frac{A}{0.04}\right)^{3/2}, \tag{1}$$

where the total system mass and A are given in solar units. In these terms, the remaining lifetime of the orbit against GW radiation losses is

$$\tau_{\mathrm{GW}} = \frac{5c^5}{256G^3}\frac{A^4}{M_1 M_2 M} = 7.13 \times 10^3\ \mathrm{yr}\left(\frac{\mu}{0.15}\right)^{-1}\left(\frac{M}{0.6}\right)^{-2}\left(\frac{A}{0.04}\right)^4, \tag{2}$$

where μ is the reduced mass of the system ($\mu = M_1 M_2/M$). We see that the lifetime of such systems during this phase is of the order of 10^5–10^{10} yr depending on the initial separation and masses. There is in addition a second identified route (Iben and Tutukov 1984*a*, *b*; 1986) by which double CO DDBs form. The primordial systems have wider primordial separations: $A \approx$ 500–1500 $R_\odot$. The qualitative difference from the route already described is that the first common-envelope stage is delayed until after the primary has exhausted helium at its center and has become an asymptotic giant branch (AGB) star. The Roche lobe overflow stage does not

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end until the star has developed a degenerate CO core. Because of the wider primordial separations, the initial separation of the CO + CO DDB will range from $A \approx 1.1$–$3.5\ R_\odot$ and beyond. The time scale for GW to bring such systems into Roche lobe contact varies from $\sim 2 \times 10^8$ to 10^{10} yr and beyond.

Iben and Tutukov (1984*a*, *b*; 1985) utilize a parameterized treatment of the effect of a common envelope in inducing orbital shrinkage and a rough estimate of the formation frequency of primordial systems as a function of initial separation and mass ratio to estimate formal frequencies of occurrence for systems of both types, obtaining a total occurrence frequency of $\nu_{\rm SN\,I} \approx 0.008\ {\rm yr}^{-1}$ in a galaxy such as ours. Because this formal frequency estimate roughly matches the observed rate of SN I explosions, and because the character of the expected explosion (light curve, total energy, absence of H and He in the spectrum, etc.) accounts so nicely for the observed properties of normal SNe I, it is very tempting to believe that the manner in which occurrence frequency estimates have been made is order-of-magnitude reliable. Iben and Tutukov therefore extend the formalism to estimate the occurrence frequency of other types of DDBs, including those that are not expected to evolve into SNe (the CO + He pairs may be produced from primordial binaries with $M_1 \approx 2$–$9\ M_\odot$, $M_2 \approx 1$–$2\ M_\odot$, and $A \approx 50$–$1000\ R_\odot$; He + He systems from those with $M_1 \approx M_2 \approx 1$–$2\ M_\odot$, and $A \approx 10$–$200\ R_\odot$). They find the total rate of DDB formation to be roughly $0.19\ {\rm yr}^{-1}$ with most of the final systems being He pairs ($3\nu_{\rm HeHe} \approx 0.15\ {\rm yr}^{-1}$). Less frequently formed are CO + He systems, $\nu_{\rm COHe} \approx 0.02\ {\rm yr}^{-1}$, CO + CO binaries with total mass less than a Chandrasekhar mass, $\nu_{\rm COCO} \approx 0.01$ yr, and CO + CO and ONe and CO binaries with total mass $> 1.4\ M_\odot$ estimated to give $\nu_{\rm SN\,I} \approx 0.01\ {\rm yr}^{-1}$.

With these frequency estimates in hand, we can estimate the average distance between nearest neighbors in our Galaxy of the various types of anticipated DDBs in what is, from the point of view of a strong periodic GW signal, the most interesting phase: the last *e*-folding time prior to the establishment of Roche-lobe contact (hence the parameterization given in equations [1] and [2]. For simplicity, we assign a fixed set of component masses to each of the major composition permutations as shown in the second column of Table 1. The third column gives the estimated frequency of formation. Next, we give the semimajor axis and orbital period of each system when Roche lobe contact is established. The GW frequency $f_{\rm GW}$ is twice the orbital frequency and is given in units of mHz. The total luminosity in GW radiation due to orbital motion is (see, e.g., Landau and Lifshitz 1951; Peters and Mathews 1963)

$$L_{\rm GW} = \frac{32G^4}{5c^5}\,\mu^2 M^3 A^{-5} = 4.76 \times 10^{36}\ {\rm ergs\ s^{-1}} \left(\frac{\mu}{0.15}\right)^2 \left(\frac{M}{0.6}\right)^3 \left(\frac{A}{0.04}\right)^{-5} . \tag{3}$$

The total luminosity in equation (3) can be used to define an angle-averaged flux:

$$F_{\rm GW} = \frac{L_{\rm GW}}{4\pi d^2} = 4.0 \times 10^{-8}\ {\rm ergs\ cm^{-2}\ s^{-1}} \left(\frac{\mu}{0.15}\right)^2 \left(\frac{M}{0.6}\right)^3 \left(\frac{A}{0.04}\right)^{-5} \left(\frac{d}{1\ {\rm kpc}}\right)^{-2} . \tag{4}$$

The luminosity near the point of Roche lobe contact for these systems is given in column seven. Estimating from equation (2), the last *e*-folding time $\tau_{\rm GW}$ prior to contact is used in conjunction with the estimated formation frequency $\nu_{\rm BIRTH}$ to give the number of systems of the various types expected in the Galaxy. We obtain d, the average distance between representatives of each type, by using a Galactic disk surface area of $A_G \approx \Pi(15\ {\rm kpc})^2 \approx 700\ ({\rm kpc})^2$ and setting $Nd^2 = A_G$. Then, the GW flux produced by a representative of each type at a distance from Earth equal to the nearest neighbor separation is found from equation (4). Finally we give the GW amplitude expected on Earth from these systems.

The GW amplitude generated by a source is in general a function of orbital orientation. It is sufficient here to use an angle and polarization averaged amplitude to make estimates and we adopt the definition used by Douglass and Braginsky (1979); whence

$$h = \left(\frac{4GF_{\rm GW}}{\pi c^3 f_{\rm GW}{}^2}\right)^{1/2} = 5.8 \times 10^{-22} \left(\frac{\mu}{0.15}\right)\left(\frac{M}{0.6}\right)\left(\frac{A}{0.04}\right)^{-1}\left(\frac{d}{1\ {\rm kpc}}\right)^{-1} . \tag{5}$$

For reference we note that this h is smaller by a multiplication factor $(\frac{3}{4})^{1/2} = 0.87$ than the characteristic amplitude defined by Thorne (1987); cf. his equation (58) and the discussion following his equation (51). The amplitudes h expected from the nearest representative of each group vary by no more than a factor of 4, despite the fact that nearest neighbor distances vary by nearly two orders of mangitude between classes.

The existence of a galactic population of DDBs has yet to be established observationally. While there is little doubt that degererate dwarfs form in binary systems, those with orbital separations greater than $\sim 3\ R_\odot$ require in excess of the Hubble time to coalesce. To play a role in SN I production, DDB progenitor systems must experience significant shrinkage in orbital separation in one or more common envelope phases.

There is observational evidence for large-scale orbital shrinkage and common envelope phases. The very compact orbital

TABLE 1

PROPERTIES OF HYPOTHESIZED CLOSE DOUBLE DEGENERATE SYSTEMS

Source	$M_{\rm WD}$ ($M_\odot$)	$\nu_{\rm birth}$ ($\rm yr^{-1}$)	$A_{\rm CONTACT}$ ($R_\odot$)	$P_{\rm CONTACT}$ (s)	$f_{\rm GW}$ (mHz)	$L_{\rm GW}$ (10^{37} ergs $\rm s^{-1}$)	GW (yr)	N (in Galaxy)	d (kpc)	$F_{\rm GW}$ (10^{-7} ergs $\rm cm^{-2}\ s^{-1}$)	h (10^{-21})
He + He	0.3 + 0.3	0.15	0.048	135	15	0.19	5.9×10^4	8800	0.28	2.1	1.7
He + CO	0.3 + 0.6	0.02	0.055	136	15	0.58	3.4×10^4	680	1.0	0.5	0.8
CO + CO	0.6 + 0.6	0.02	0.033	55	37	40	1.6×10^3	33	4.6	1.6	0.6
SN I	0.8 + 0.8	0.01	0.027	35	57	460	310	3	15	1.7	0.4

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parameters of cataclysmic variables probably stem these effects. Indeed, perhaps the most compelling evidence comes from the system Abell 41 (Grauer and Bond 1983) which has been shown to be a short period, 2 hr 43 minutes, precontact binary inside a planetary nebula shell. The binary components are similar to cataclysmic variable components. With their close separation, contact will be established in $\sim 2 \times 10^9$ yr due to GW radiation.

There is also the recent discovery of the 11.4 minute, ultra–short period binary associated with the X-ray source 4U 1820−30 in the globular cluster NGC 6624 (Stella, Priedhorsky, and White 1986). These authors conclude the system is most likely a neutron star–white dwarf binary in the process of mass transfer. While this system might form in a scenario similar to those outlined here, it is difficult to see how this would occur in a globular cluster; see Bailyn and Grindlay (1987) who suggest 4U 1820−30 resulted from tidal capture between a neutron star and low-mass main-sequence star.

Two systems have been widely discussed as degenerate dwarf binaries: HZ 29 (AM CVn) (Smak 1967; Ostriker and Hesser 1968; Warner and Robinson 1972; Faulkner, Flannery, and Warner 1972; Robinson and Faulkner 1975; Patterson *et al.* 1979; Solheim *et al.* 1984) and G61-29 (GP Com) (Burbidge and Strittmatter 1971; Warner 1972; Smak 1975; Nather, Robinson and Stover 1981). Both stars show photoelectric and spectroscopic variability. G61-29 appears firmly established as a 46.5 minute binary with two helium degenerate dwarf components. The secondary has mass $\sim 0.02\ M_\odot$ while the primary mass is uncertain but is of the order of one solar mass (Nather, Robinson, and Stover 1981). The situation with regard to HZ 29 is not as clear. This system appears to be binary in nature with an even shorter orbital period of 17.5 minutes (Smak 1967; Ostriker and Hesser 1968; Warner and Robinson 1972; Solheim *et al.* 1984). It is difficult to reach firm conclusions about HZ 29 due to the observational uncertainties such as the large phase jitter and uncertainty in the sign of the suspected period changes (Solheim *et al.* 1984). Iben and Tutukov (1987) argue that HZ 29 may consist of a core helium-burning star donating mass through its Roche lobe to a carbon-oxygen white dwarf.

Finally, there is considerable difficulty in identifying precontact DDBs, which will largely look like one dwarf. Given the strong dependence of system lifetime (2) on separation, A, it is most probable to find a DDB near its initial (wide) orbital separation following the last common envelope phase. The compactness of the components argues that there will be no appreciable light curve and eclipses will be extremely rare and brief. The best strategy might be to look for periodicity in the Doppler shift of spectral lines in line-bearing dwarfs (see Robinson and Shafter 1987).

III. THE DETECTABILITY OF PERIODIC EMISSION FROM DEGENERATE DWARF BINARIES

In light of the high potential birthrate of DDBs, we might expect these stars to be an important source of detectable signals in a low-frequency GW antenna. We examine here the properties of such signals and their detectability by a recently proposed design for a space-based laser interferometer (Faller and Bender 1984; Faller *et al.* 1984; and more recently Hils *et al.* 1987) being explored at the Joint Institute for Laboratory Astrophysics (henceforth called the JILA antenna). The present concept for the JILA antenna consists of three spacecraft flying in tandem, providing two interferometer arms with a 10^6 km baseline. The proposed sensitivity over the frequency band 10^{-4} to 10^{-1} Hz, limited by photon shot noise, amounts to a power spectral density of $S_h(f) = 10^{-40}$ Hz^{-1}, giving an rms amplitude of $h_{\rm sens} = 10^{-23}$ for a $\tau_{\rm INT} = 10^6$ s integration time. The sensitivity amplitude degrades as $h_{\rm sens} \propto f^{-3}$ below $f = 10^{-4}$ Hz due to spurious accelerations on the free masses. Above $f = 10^{-1}$ Hz, the sensitivity degrades as $h_{\rm sens} \propto f$ as the signal wavelength becomes shorter than the interferometer baseline. This sensitivity curve is shown plotted in Figure 2*a* for $\tau_{\rm INT} = 10^6$ s.

One of the crucial aspects of DDBs is their known evolutionary route due to GW losses prior to merger. This implies that their distribution over orbital separation, or equivalently f, can be obtained given a total birth rate ν_T. If the merging of DDBs is associated with the production of SNe I, then, we may take, $\nu_T \approx 0.15\ \mathrm{yr}^{-1}$. This is in contrast to the distributions of cataclysmic variables (CVs) and W UMa stars over f, where little *a priori* knowledge exists of their evolutionary behavior and the distributions must be optically observed.

The distribution of DDBs does have the complication that not all such binaries will be born with large separations. Rather, as Iben and Tutukov (1984*a*, *b*) have argued, these stars will emerge from the last common envelope stage with separations ranging from 0.13 to 3.5 $R_\odot$. Because of the rudimentary nature of our understanding of the common envelope phase, we have little *a priori* knowledge of how the initial separations will be distributed. We assume here the birthrate density to be logarithmic in a and f: $d\nu = cd \ln f$ with c a constant. The total birth rate ν_T determines the constant

$$\nu_T = c \int_{f_0}^{f_1} d \ln f = c \ln \left(\frac{f_1}{f_0} \right), \tag{6}$$

where $f_0 \approx 2 \times 10^{-5}$ Hz and $f_1 \approx 3 \times 10^{-3}$ Hz correspond to the bounding initial separations of $A \approx 3.5\ R_\odot$ and $A \approx 0.13\ R_\odot$, respectively. The birth rate for all stars with initial frequency less than some f is

$$\nu(f) = \nu_T \ln \left(\frac{f}{f_0} \right) \Big/ \ln \left(\frac{f_1}{f_0} \right), \tag{7}$$

with $\nu(f) = \nu_T$ for $f > f_1$. The distribution of DDBs over f can be obtained using the evolutionary time scale $\tau_{\rm GW}$ from equation (2):

$$dn(f) = \nu(f) d\tau_{\rm GW} = \tfrac{5}{96} \pi^{-8/3} c^5 G^{-5/3} \mu^{-1} M^{-2/3} \nu(f) f^{-11/3} (-df)\ . \tag{8}$$

This distribution ranges in frequency from f_0 to some f_m which is the (highest) frequency that occurs at the time of merger of the binary.

Assuming DDBs form a Galactic disk population allows their distribution over GW amplitude to be determined. Considering the potentially large uncertainty in the birth rate ν_T, we merely assume this population has associated with it a scale height H and that the disk extends about us to some radius R_G (i.e., we ignore the concentration of sources toward the Galactic center). It is important,

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as will be discussed, to consider the spherical spatial distribution that occurs on length scales $r \lesssim H \approx 200$ pc. The fraction of the birth rate in an interval dr at distance r is

$$dv(f) = \frac{v(f)}{\pi R_G{}^2(2H)} \cdot 4\pi r^2 dr \quad , \qquad 0 < r < H$$

$$= \frac{v(f)}{\pi R_G{}^2} \cdot 2\pi r dr \qquad , \qquad H < r < R_G \; . \tag{9}$$

The dependence on radius can be converted to dependence on amplitude h using (5) and (8) can be used in (9) in place of $v(f)$ to give the distribution of DDBs over f and h. Implicit in the use of (5) and (8) are particular values for the total mass and reduced mass. In principle one should broaden the distribution to include a two-parameter mass distribution $\Phi(M, \mu)dMd\mu$ for the relative frequency of occurrence of different mass and mass ratio DDBs. For our purposes, these subtleties are of relatively minor importance in the determination of the detectability of these sources. Of much greater importance is the strong dependence on v_T and the detector sensitivity. Accordingly, we take a single (low) value of the mass ($M \approx 0.6\ M_\odot$, $\mu \approx 0.15\ M_\odot$) typical of the expectedly more abundant DDBs.

The distribution (9) breaks at $r \approx H$. The amplitude for binaries at this distance is

$$h_H = (\tfrac{32}{5})^{1/2}\pi^{2/3}G^{5/3}c^{-4}\mu M^{2/3}f^{2/3}H^{-1} \; , \tag{10a}$$

$$h_H = 4.1 \times 10^{-22}\left(\frac{\mu}{0.15}\right)\left(\frac{M}{0.6}\right)^{2/3}\left(\frac{f}{1\ \text{mHz}}\right)^{2/3}\left(\frac{H}{200\ \text{pc}}\right)^{-1} \; , \tag{10b}$$

where M and μ are in solar units. This amplitude roughly determines the break point for a distribution over h. Combining (5), (8), and (9) we have

$$dn(f, h) = \begin{cases} K_v f^{-5/3}h^{-4}dfdh & h > h_H \\ K_D f^{-7/3}h^{-3}dfdh & h < h_H \end{cases} \tag{11a}$$

with

$$K_v = \tfrac{8}{3}(\tfrac{2}{5})^{1/2}\pi^{-2/3}G^{10/3}c^{-7}\mu^2 M^{4/3}R_G{}^{-2}H^{-1}v(f) \; , \tag{11b}$$

$$K_D = \tfrac{2}{3}\pi^{-4/3}G^{5/3}c^{-3}\mu M^{2/3}R_G{}^{-2}v(f) \; , \tag{11c}$$

for the full number distribution. This distribution has contributions in frequency from f_0 to f_m. It extends in amplitude down to the most distant (weakest) binaries, which have amplitudes

$$h_W = 7.5 \times 10^{-24}\left(\frac{\mu}{0.15}\right)\left(\frac{M}{0.6}\right)^{2/3}\left(\frac{f}{1\ \text{mHz}}\right)^{2/3}\left(\frac{R_G}{10\ \text{kpc}}\right)^{-1} \; . \tag{12}$$

These limits will not be sharp if a range of binary masses are considered. As Clark (1979) and others have stressed, it is convenient to give the distribution over logarithmic frequency and amplitude intervals. Rewriting (11) we have

$$\frac{dn}{d\log f \cdot d\log h} = 1.93\left(\frac{\mu}{0.15}\right)^2\left(\frac{M}{0.6}\right)^{4/3}\left(\frac{R_G}{10\ \text{kpc}}\right)^{-2}\left(\frac{H}{200\ \text{pc}}\right)^{-1}\left(\frac{v(f)}{0.15\ \text{yr}^{-1}}\right)\left(\frac{f}{1\ \text{mHz}}\right)^{-2/3}\left(\frac{h}{10^{-20}}\right)^{-3}$$

$$= 51.4\left(\frac{\mu}{0.15}\right)\left(\frac{M}{0.6}\right)^{2/3}\left(\frac{R_G}{10\ \text{kpc}}\right)^{-2}\left(\frac{v(f)}{0.15\ \text{yr}^{-1}}\right)\left(\frac{f}{1\ \text{mHz}}\right)^{-4/3}\left(\frac{h}{10^{-20}}\right)^{-2} \; . \tag{13}$$

Contours of constant number density derived from (24) are shown in Figure 1. The transition from the more distant disk to the local spherical population is evident. The distribution (11), or (13), contains all the information on DDBs necessary for discussing their detectability.

It is clear by the amplitude calculated from (10) that the proposed detector sensitivity is sufficient to see some individual binaries, particularly higher frequency ones. A more serious issue is that of resolving the individual signals.

With a birthrate as large as proposed here, $v_T \approx 0.15\ \text{yr}^{-1}$, these periodic signals will overlap in frequency space, even given integration times of $\sim 10^6$ s. The elementary bandwidth of the detector is

$$\Delta f_{\text{INT}} \approx \tau_{\text{INT}}{}^{-1} \; . \tag{14}$$

We integrate the distribution (11) in amplitude down to a limiting value and over a bandwidth Δf_{INT}. This computes the mean number of sources per elementary bandwidth in a volume characterized by this limiting amplitude. If a mean number of unity of sources is obtained at an amplitude h_n greater than h_w, i.e.,

$$\int_{h_n}^{\infty}\left(\frac{dn}{dfdh}\right)dh \cdot \Delta f_{\text{INT}} = 1 \; , \tag{15}$$

then the sources overlap for all those with $h_n > h > h_w$. If $h_n > h_w$ does not exist in some band, the periodic signals are individually resolved for these frequencies and integration time.

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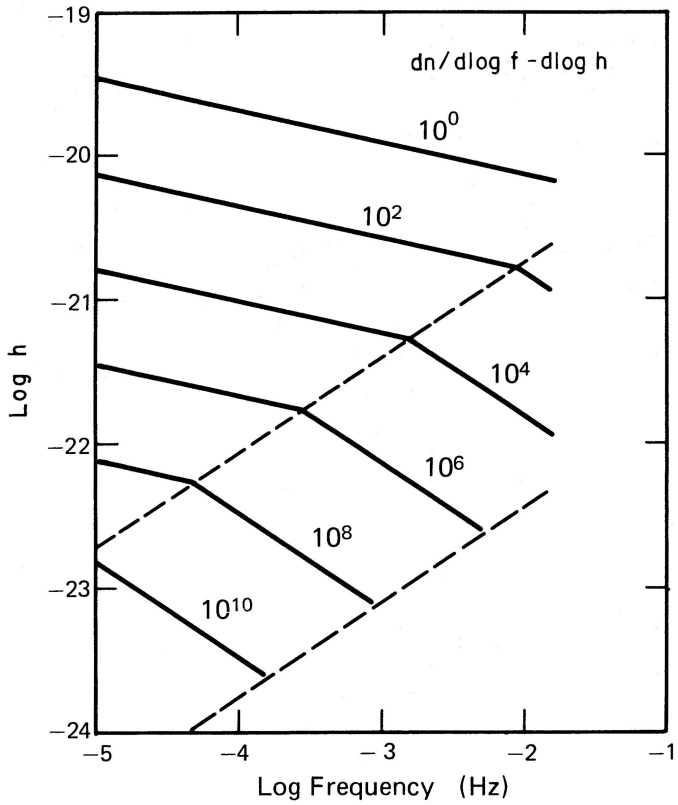


FIG. 1.—Contours of the number distribution $dn/(d \log f d \log h)$ for DDBs assuming a total birthrate of $\nu_T \approx 0.15$ yr^{-1}. The calculation assumes a disk population of DDBs. The transition from disk distribution to local spherical distribution is evidenced by the break in the contours.

To find $h_n(f)$, we first note that a critical frequency f_b exists due to the transition in the number distribution at $h = h_H$. This occurs at the frequency for which $h_n = h_H$, or

$$\int_{h_H}^{\infty} K_v f^{-5/3} h^{-4} dh \Delta f_{\rm INT} = 1 \, . \tag{16}$$

This gives a critical frequency of

$$f_b^{1/3} = \tfrac{5}{144} \pi^{-8/3} G^{-5/3} c^5 \mu^{-1} M^{-2/3} R_G^{-2} H^2 \nu_T \Delta f_{\rm INT} \, , \tag{17}$$

if $\nu(f_b) \approx \nu_T$. Proceeding with the integrations gives

$$h_n^3 = \tfrac{8}{9}(\tfrac{2}{5})^{1/2} \pi^{-2/3} G^{10/3} c^{-7} \mu^2 M^{4/3} R_G^{-2} H^{-1} \nu(f) \Delta f_{\rm INT} f^{-5/3} \qquad f < f_b \tag{18a}$$

$$h_n^2 \approx \tfrac{1}{3} \pi^{-4/3} G^{5/3} c^{-3} \mu M^{2/3} R_G^{-2} \nu(f) \Delta f_{\rm INT} f^{-7/3} \qquad f \gg f_b \, . \tag{18b}$$

This overlap amplitude is plotted in Figures 2*a* and 2*b* for two values of the detector resolution. Increasing the detector resolution decreases the overlap amplitude for $f > f_b$ at the same rate at which $h_{\rm sens}$ decreases. The break frequency is clearly evident and shifts toward lower frequencies as $\Delta f_{\rm INT}$ decreases.

A second important frequency is that for which $h_n = h_w$. Above this "clearing" frequency the sources no longer overlap and are fully resolved with the given integration time (if they are above the detector noise level). This frequency can be found to be

$$f_c = 11.8 \text{ mHz} \left(\frac{\mu}{0.15}\right)^{-3/11} \left(\frac{M}{0.6}\right)^{-2/11} \left[\frac{\nu(f)}{0.15 \text{ yr}^{-1}}\right]^{3/11} \left(\frac{\Delta f_{\rm INT}}{10^{-6}}\right)^{3/11} \, . \tag{19}$$

This frequency is shown in Figures 2*a* and 2*b*. We will discuss the observational significance of f_c presently.

While knowledge of $h_n(f)$ is necessary to proceed in the calculation, $h_n(f)$ is not directly observable. In those bands in which they overlap, source signals will incoherently sum to produce a noise signal or "continuum" emission. This will swamp all but occasional individual periodic signals in these bands. While this continuum emission looks like a stochastic signal, it can always be eliminated with sufficient resolution. Hence we avoid discussing it in terms of its power spectral density and instead characterize it by an equivalent rms amplitude $h_c(f)$. However, we may always recover the power spectral density through the expression $S_h(f) = h_c^2 \Delta f_{\rm INT}^{-1}$.

Since flux is proportional to h^2 an incoherent sum yields

$$h_c^2 = \int h^2 \left(\frac{dn}{dhdf}\right) dhdf \, . \tag{20}$$

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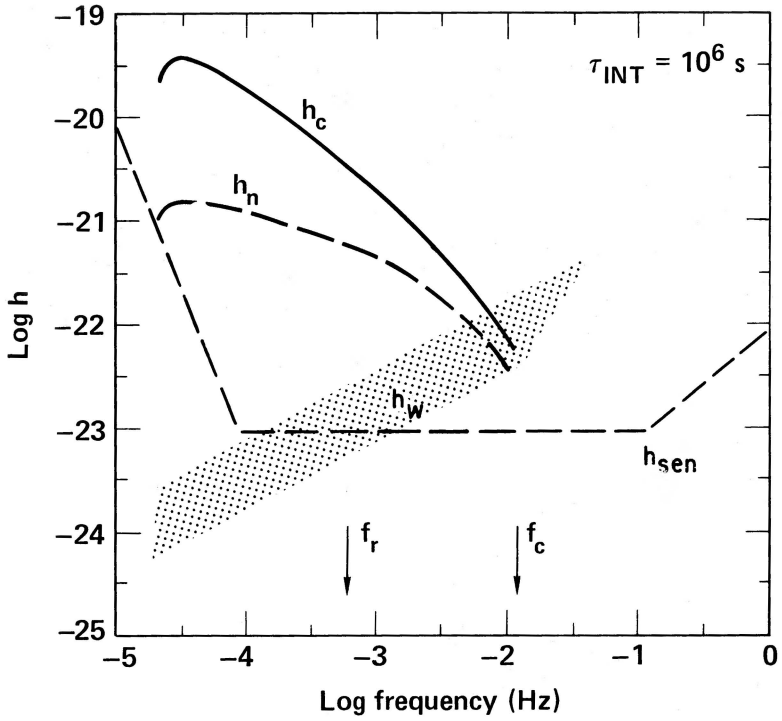


FIG. 2a

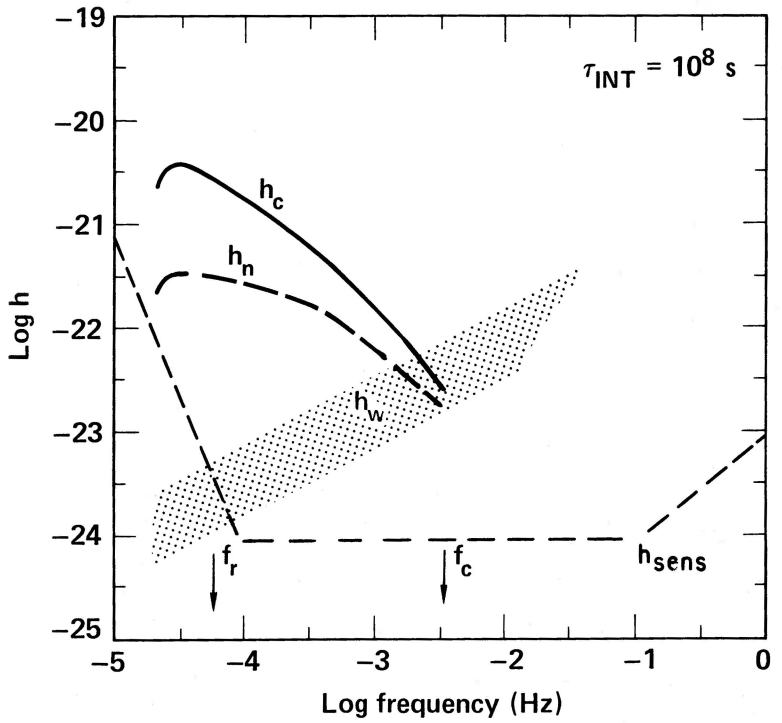


FIG. 2b

FIG. 2.—(*a*) The proposed detector sensitivity h_{sens} versus frequency for an integration time of 10^6 s. The amplitudes of the most distant galactic sources, spread by differences in mass, are indicated by the shaded region. Closer binaries will have higher amplitudes. Those with amplitudes above h_{sens} are potentially detectable. Curve h_c indicates a continuum signal from the incoherent sum of unresolved binaries at this length of integration. For an individual source to be resolved, its amplitude must lie above h_c. f_c indicates the frequency above which all sources are resolved. f_r is the frequency below which essentially no binaries are resolved above the continuum. (*b*) Same as (*a*) except for an integration time of 10^8 s. Now substantially more sources are detectable and these are more easily resolved above the reduced level of the continuum.

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Using (11), we obtain

$$h_c^2 = K_v f^{-5/3} \Delta f_{\rm INT} h_H^{-1} \left[1 + \ln \left(\frac{h_*}{h_w} \right) \right], \tag{21}$$

where $h_* = \min(h_n, h_H)$. The logarithmic factor can be simplified by writing $\ln(h_*/h_w) = \ln(h_*/h_H) + \ln(h_H/h_w)$, and noting that $\ln(h_H/h_w) = 3.91 + \ln(R_G/10\ \text{kpc}) - \ln(H/200\ \text{pc})$. This allows the continuum amplitude to be expressed as

$$h_c = 2.18 \times 10^{-21} \left(\frac{\mu}{0.15} \right)^{1/2} \left(\frac{M}{0.6} \right)^{1/3} \left(\frac{v_T}{0.15\ \text{yr}^{-1}} \right)^{1/2} \left(\frac{R_G}{10\ \text{kpc}} \right)^{-1} \left(\frac{f}{1\ \text{mHz}} \right)^{-7/6} \left(\frac{\Delta f_{\rm INT}}{10^{-6}} \right)^{1/2} I^{1/2}, \tag{22a}$$

where

$$I = 1.0 + 0.204 \left[\ln \left(\frac{h_*}{h_H} \right) + \ln \left(\frac{R_G}{10\ \text{kpc}} \right) - \ln \left(\frac{H}{200\ \text{pc}} \right) \right]. \tag{22b}$$

This "background" amplitude is shown plotted in Figures 2*a* and 2*b* for two different detector integration times. Also indicated are the respective values of the clearing frequency f_c. It is evident that, for $\tau_{\rm INT} > 10^6$ s, the most interesting band for DDBs, that from 10 to 100 mHz associated with the last *e*-folding before merging, is fully resolved. Emphasizing the range of possible binary masses, we have indicated (*shaded region*) the amplitudes for the weakest sources. It is also clear from Figure 2*a* that, even for $\tau_{\rm INT} = 10^6$ s, nearly all binaries with $f > f_c$ are detectable above the detector noise level. With a 10^8 s (~ 3 yr) integration time (probably near the maximum that can be expected in view of spacecraft lifetime), all binaries with frequencies above ~ 3 mHz should be detected.

Another consideration facing detection of DDBs concerns the orbital changes due to GW emission. The rate of change of a binary period due to GW losses is

$$\dot{P} = \tfrac{192}{5} \pi^{8/3} c^{-5} G^{5/3} \mu M^{2/3} f^{5/3},$$

or

$$\dot{P} = 1.23 \times 10^{-12}\ \text{ss}^{-1} \left(\frac{\mu}{0.15} \right) \left(\frac{M}{0.6} \right)^{2/3} \left(\frac{f}{1\ \text{mHz}} \right)^{5/3}. \tag{23}$$

Since the detector bandwidth $\Delta f_{\rm INT}$ decreases with increasing integration time, the intrinsic width of the source grows due to its steady shift in frequency. Thus, we may set

$$\tau_{\rm INT}^{\rm limit} = 1.3 \times 10^9\ \text{s} \left(\frac{\mu}{0.15} \right)^{-1/2} \left(\frac{M}{0.6} \right)^{-1/3} \left(\frac{f}{1\ \text{mHz}} \right)^{-11/6} \tag{24}$$

as a rough limit on useful integration time. A more exact limit would require a sophisticated signal processing such as has been discussed for terrestrial interferometers using matched filtering (see Schutz 1986; Smith 1986). A plot of the limit given by (24) as a function of frequency is given in Figure 3 for several values of total mass. For integration times between 10^6 and 10^8 s condition (24) becomes a consideration for binaries in the frequency range 10–100 mHz. Over a period of several years, this should allow measurement of the period change in these rapidly evolving systems.

We next consider detection of individual sources above the continuum for frequencies $f < f_c$. We will consider that an individual source is resolved if its amplitude satisfies $h \geq h_c$. How many such sources can be observed depends on the mean number per elementary bandwidth with amplitude at or above h_c:

$$n(h_c) = \int_{h_c}^{\infty} \left(\frac{dn}{df dh} \right) dh \Delta f_{\rm INT}. \tag{25}$$

For $f < f_c$, $n(h_c)$ is always less than one. At low frequencies $f < f_b$ evaluation of (25) yields

$$n(h_c) = 1.17 \times 10^{-2} \left(\frac{\mu}{0.15} \right)^{1/2} \left(\frac{M}{0.6} \right)^{1/3} \left(\frac{v_T}{0.15\ \text{yr}^{-1}} \right)^{-1/2} \left(\frac{R_G}{10\ \text{kpc}} \right) \left(\frac{H}{200\ \text{pc}} \right)^{-1} \left(\frac{\Delta f_{\rm INT}}{10^{-6}} \right)^{-1/2} \left(\frac{f}{1\ \text{mHz}} \right)^{11/6}. \tag{26}$$

For higher frequencies the result is more complicated and a numerical evaluation is required.

The probability for finding an integer number of sources, $N = 1, 2, 3\ldots$, above the continuum in any elementary band $\Delta f_{\rm INT}$ is determined by the Poisson distribution with mean value $n(h_c)$:

$$P_{n(h_c)}(N) = \frac{1}{N!} n(h_c)^N e^{-n(h_c)}. \tag{27}$$

Since the mean satisfies $n(h_c) \ll 1$ we need only be concerned with $N = 1$ and we obtain

$$P_{n(h_c)}(1) = n(h_c) e^{-n(h_c)}. \tag{28}$$

This probability per elementary bandwidth can be converted to an expected number of resolved sources per *e*-fold in frequency:

$$N_r(f) = P_{n(h_c)}(1) \Delta f_{\rm INT}^{-1} f. \tag{29}$$

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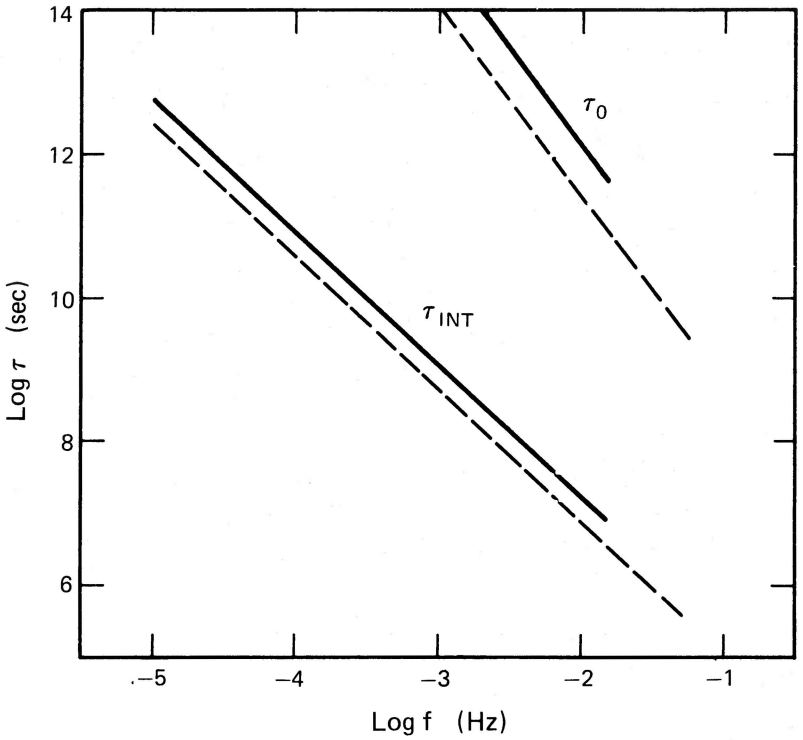


FIG. 3.—The intrinsic width of a DDB source in frequency space due to orbital separation shrinkage sets a limit on useful integration time, in the absence of more sophisticated matched filtering. This limit on τ_{INT} for binaries of different frequencies is shown, both for systems with total mass = 0.6 $M_\odot$ (*solid line*) and total mass = 1.6 $M_\odot$ (*dashed line*). Also plotted are the respective remaining system lifetimes τ_0.

Evaluation of this probability shows progressively fewer sources are resolved at lower frequencies. Below a certain frequency, f_r, defined by $N_r(f_r) = 1$, there are essentially no binaries resolvable above the continuum. This frequency can be approximately expressed as

$$f_r = 0.61 \text{ mHz} \left(\frac{\mu}{0.15}\right)^{-3/17} \left(\frac{M}{0.6}\right)^{-2/17} \left(\frac{v_T}{0.15 \text{ yr}^{-1}}\right)^{3/17} \left(\frac{R_G}{10 \text{ kpc}}\right)^{-6/17} \left(\frac{H}{200 \text{ pc}}\right)^{6/17} \left(\frac{\Delta f_{INT}}{10^{-6}}\right)^{9/17} \quad (30)$$

and is indicated in Figures 2*a* and 2*b*.

Even for integration times of the order of years, only a small fraction of all DDBs could be observed above the continuum. It would be useful if this limit could be overcome. Indeed, since it is not possible to shield the detector like a radiometer, there is some concern about the ability to identify the difference between a Galactic background signal and intrinsic detector noise (Weiss 1979). However, the JILA antenna design would produce a broad antenna pattern with sharp nulls in certain directions. As orientation of the interferometer precesses during its orbital motion, these null directions in the beam should sweep through the Galactic plane producing a dramatic effect in the continuum signal on shorter (10^6 s) time scales (Bender 1985). During these periods, sources at high Galactic latitude that are normally buried in the background may become apparent. From the standpoint of astronomy, further enhancements in the directionality of the detector itself would be desirable. This might be accomplished by the use of a second interferometer (or an additional arm). If two independent time series are collected, it might be possible to achieve high directionality by analyzing correlations with different lag times. This type of triangulation is envisioned in plans for the use of terrestrial laser interferometers. The degree of directionality is a strong function of the detector baseline, number of arms, and signal-to-noise ratio (Schutz 1986). If ground-based interferometers are a guide, angle measurements on the order of a few degrees may be possible.

IV. CONCLUSIONS

We have discussed the implications for gravitational wave astronomy of a recently hypothesized population of double degenerate dwarf binaries. Theoretically, these binaries are thought to be good candidate systems for Type I supernova progenitors. In theoretical studies of the stellar evolution of intermediate-mass binary systems, remnant binaries containing two degenerate dwarfs are a frequent outcome, with a Galactic birth rate perhaps as high as $v_T \approx 0.15 \text{ yr}^{-1}$.

Observationally there is as yet only circumstantial evidence for a large population of DDBs. A number of ultra–short period systems, such as HZ 29, G61-29, 4U 1820−30, Abell 41, and others, suggest that the important facet viewed necessary for massive orbital separation shrinkage, common envelope phases, do occur. The observational difficulties in detecting precontact binaries is formidable since there is little to distinguish these from single degenerate dwarfs, and it is most probable to find these at their widest separations. If DDBs remain viable theoretical candidates for producing SNe I, then it may be that future low-frequency gravitational wave astronomy observations will provide important constraints on supernova theories.

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We have discussed one such low-frequency GW detection scheme employing space-based laser interferometers. The proposed sensitivity is adequate to detect the presence of a large population of DDBs as well as to detect individual sources. If such a detector can be built, several other classes of Galactic close binary systems will be accessible to study, including binary neutron stars, cataclysmic variables, and W UMa stars. Similar conclusions have been drawn, as we have recently been made aware, in two other papers by Lipunov and Postnov (1987) and Hils *et al.* (1987).

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