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AN UPPER LIMIT TO THE SPACE DENSITY OF SHORT-PERIOD, NONINTERACTING BINARY WHITE DWARFS

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ABSTRACT

We have searched for short-period, detached binary stars in which both stars are white dwarfs by looking for radial velocity variations in spectroscopically identified DA and DB white dwarfs. The search was sensitive to binaries with orbital periods between 30 s and 3 hr and, within that range, we would have detected roughly 90% of all binaries, depending on the distribution of their orbital periods, mass ratios, and spectral types. We observed 44 stars without finding any binaries. The fraction of white dwarfs that are binaries is less than 1/20 with a 90% probability and less than 1/37 with a 70% probability. Other surveys sensitive to longer periods have also failed to find a large population of binary white dwarfs. The space density of binary white dwarfs is too low to account for the rate of Type I supernovae in the Galaxy and too low to agree comfortably with recent estimates of their numbers from theoretical calculations of the evolution of close binaries. Binary white dwarfs are the dominant source of the background gravitational waves at periods between about 30 s and 1 hr. The background is likely to be much lower than previously thought.

Subject headings: stars: binaries — stars: stellar statistics — stars: supernovae — stars: white dwarfs

I. INTRODUCTION

Short-period binary white dwarfs are not unknown. G61–29 is a binary white dwarf and HZ 29, PG 1346+082, and V803 Cen might be also (Nather, Robinson, and Stover 1981; Solheim *et al.* 1984; O'Donoghue, Menzies, and Hill 1987; Wood *et al.* 1987). All these systems are interacting: mass is being transferred from one star to the other in a stream through the inner Lagrangian point. Detached pairs of white dwarfs have also been found but they are all visual binaries with long orbital periods (e.g., the six binaries discussed by Greenstein 1986). No short-period, detached binary white dwarfs have ever been found.

Short-period, detached systems should exist, however. Interacting pairs like G61–29 should have noninteracting progenitors. The binary system LB 3459, which has an orbital period of 6.3 hr, contains of a pair of hot subdwarfs that will cool to become a pair of white dwarfs (Kilkenny, Hill, and Penfold 1981). All recent theoretical calculations of the evolution of close binaries predict that many Algol-like binaries will turn into short-period, detached binary white dwarfs after passing through a stage of common envelope evolution (Webbink 1984; Iben and Tutukov 1984). Paczyński (1985) has speculated that as many as one in 10 white dwarfs could be binaries.

If these binaries do exist in such large numbers, they would be extremely important. They would be the dominant source of background gravitational radiation at periods between roughly 0.5 minutes and 1 hr (Hils *et al.* 1986). It has been proposed that high-mass binary white dwarfs could be the long-sought progenitors of Type I supernovae if their space density is high enough (Iben and Tutukov 1984; for an opposing view, see Saio and Nomoto 1985). The properties, space densities, and period distribution of the binary white dwarfs would also provide direct tests of theoretical studies of the late stages in the evolution of close binaries, particularly those stages involving common envelope evolution.

Surveys have been made for long-period binary white dwarfs (e.g., Greenstein 1986) but to our knowledge, no concerted effort has been made to find short-period, noninteracting binary white dwarfs. We undertook, therefore, a search for these systems. This paper reports the results of our efforts.

II. OBSERVATIONAL TECHNIQUE

We searched for binary white dwarfs by looking for radial velocity variations among spectroscopically identified DA and DB white dwarfs. We looked for the radial velocity variations by measuring the light curves of the white dwarfs through narrow-band filters whose bandpasses lay in the wings of an absorption line, the Hγ line if the white dwarf was a DA white dwarf and the He I λ4471 line if the white dwarf was a DB white dwarf. If the radial velocity of the white dwarf varies, the center of the absorption line moves toward or away from the filter bandpass, decreasing or increasing the flux of light through the filters. Orbital radial velocity variations can be detected from periodic variations in the filtered light curve. There are two principal advantages to this method for detecting radial velocity variations compared to normal spectroscopic methods. First, since our integration times were short, we could search for radial velocity variations at periods as short as 30 s. Second, since data reduction takes much less time for photometry than for spectroscopy, we were able to increase the number of stars in the survey.

The basic equation for the effect of the filters on the flux from a white dwarf is

$$F(\Lambda) = \int I(\lambda - \Lambda)T(\lambda)d\lambda \ , \quad (1)$$

where $F(\Lambda)$ is the flux of light coming through the filter when the stellar spectrum has been shifted by an amount Λ, $I(\lambda - \Lambda)$ is the flux in the stellar spectrum at wavelength $\lambda - \Lambda$, and $T(\lambda)$ is the transmission of the filter at wavelength λ. Expanding equation (1) to first order about $\Lambda = 0$, we have

$$F(\Delta\Lambda) = \int I(\lambda)T(\lambda)d\lambda - \Delta\Lambda \int I(\lambda) \frac{\partial \ln I(\lambda)}{\partial \lambda} T(\lambda)d\lambda \ , \quad (2)$$

where the derivative is evaluated at $\Lambda = 0$. If $\partial \ln I(\lambda)/\partial\lambda$ is constant over the width of the filter, which it will be for a sufficiently narrow filter, then

$$F(\Delta\Lambda) = F(0)\left[1 - \Delta\Lambda \frac{\partial \ln I(\lambda)}{\partial\lambda}\right], \tag{3}$$

which simplifies to

$$\frac{\Delta F}{F(0)} = -\Delta\Lambda \frac{\partial \ln I(\lambda)}{\partial\lambda}, \tag{4}$$

where $\Delta F = F(\Delta\Lambda) - F(0)$. Equation (4) shows that the details of the filter transmission curve are not important as long as the filter has a narrow bandpass and as long as the shift in the spectrum is not too large. Therefore, the only parameter necessary to convert an observed change in intensity to a change in wavelength is the slope of the spectrum in the region of the filter.

The wings of the Hγ and He I λ4471 lines can extend up to 100 Å from the line centers in the spectra of white dwarfs. Since our method is more sensitive to radial velocity variations if the slope of the line wings is large and since large slopes are restricted to parts of the line wings near the line centers, we chose filters that were much narrower than 100 Å and had central wavelengths close to the line centers. The properties of the filters we had available are shown in Table 1. In retrospect, the Hγ filters were chosen well but the He I λ4471 filters were narrower than necessary, and the consequent loss of photons restricted us to observing only the few brightest DB white dwarfs.

The derivative $\partial \ln I/\partial\lambda$ depends on the temperature and gravity of the white dwarf and, to be perfectly correct, should be measured from the observed spectrum of the individual white dwarfs. It is not necessary to be so exact. All white dwarfs have nearly the same surface gravity, $\log g \approx 8.0$ (Oke, Weidemann, and Koester 1984; Weidemann and Koester 1984), and, over the range of temperatures in which the bulk of DA and DB white dwarfs are found, the derivative is insensitive to temperature. Table 2 shows values of $\partial \ln I/\partial\lambda$ for $\log g = 8.0$ taken from theoretical line profiles. We used the profiles calculated by Koester (1980) for the He I λ4471 line and the profiles calculated by Wickramasinghe (1972) for Hγ. For Hγ the derivative varies by less than 30% between 10,000 K and 20,000 K, and for He I λ4471 it varies by less than 15% between 16,000 K and 24,000 K. Thus, use of intermediate values for the derivative will give radial velocities correct to within 15% unless the white dwarf has an extreme temperature.

After some experimentation we chose to use just the blue wing filters and to observe continuously through them (except for sky measurements) because the McDonald Observatory high-speed photometer can intergrate through only one filter at a time and because signal is lost when changing filters. With this choice, good values for $\partial \ln I/\partial\lambda$ are 0.016 for the Hγ line and 0.015 for the He I λ4471 line. The reader can easily correct our limits on the amplitudes of the radial velocity variations if better values of the derivatives become available for individual stars.

TABLE 1

Properties of the Narrow-Band Filters

Spectral Feature	Wavelength (Å)	FWHM (Å)	Peak Transmission (%)
Hγ blue wing	4322	24	61
Hγ red wing	4356	26	52
He I λ4471 blue wing	4465	13	53
He I λ4471 red wing	4486	14	53

TABLE 2

Slopes of the Line Wings

Spectral Type (Spectral Feature)	Temperature (K)	$\partial \ln I/\partial\lambda$ ($Å^{-1}$) Blue Wing[a]	Red Wing[a]
DA (Hγ)	10,000	−0.0139	0.0186
	12,000	−0.0177	0.0177
	20,000	−0.0134	0.0134
DB (He I λ4471)	16,000	...	0.0122
	20,000	−0.0148	0.0113
	24,000	...	0.0105

[a] The wavelengths correspond to the central wavelengths of the filters listed in Table 1.

Complications arise if the two white dwarfs in a binary have comparable brightness. If two stars contribute to the observed spectrum, then by an obvious generalization of equations (1) through (4), the fractional change in the observed flux is given by

$$\frac{\Delta F}{F(0)} = -\left[\frac{F_1}{F(0)}\right]\Delta\Lambda_1 \frac{\partial \ln I_1(\lambda)}{\partial\lambda} - \left[\frac{F_2}{F(0)}\right]\Delta\Lambda_2 \frac{\partial \ln I_2(\lambda)}{\partial\lambda}, \tag{5}$$

where the subscripts refer to the first and second star and $F(0) = F_1(0) + F_2(0)$. The spectra of white dwarfs are sufficiently simple and uniform that we need examine only two possibilities. If the two stars have different spectral types, the absorption lines of one star will fall on the continuum of the other star, so we can set $\partial \ln I_2(\lambda)/\partial\lambda \approx 0$. In effect, the absorption line is diluted by the continuum light and the slope of its wings and the observed flux variation are reduced by the factor $F_1/(F_1 + F_2)$.

If the two stars have the same spectral type, the profiles of their absorption lines are similar and we can set $\partial \ln I_1(\lambda)/\partial\lambda \approx \partial \ln I_2(\lambda)/\partial\lambda \approx \partial \ln I(\lambda)/\partial\lambda$. Equation (5) becomes

$$\frac{\Delta F}{F(0)} = -\left[\frac{F_1\Delta\Lambda_1 + F_2\Delta\Lambda_2}{F(0)}\right]\frac{\partial \ln I(\lambda)}{\partial\lambda}. \tag{6}$$

Thus, the observed flux variation corresponds to a weighted average of the radial velocity variations. Since $\Delta\Lambda_1$ and $\Delta\Lambda_2$ always have opposite signs, averaging can reduce the observed flux variations greatly.

The effect of dilution and averaging *must* be included in the data analysis as they can significantly reduce the sensitivity to radial velocity variations. A proper statistical analysis of their effect would require the mass and luminosity distributions for white dwarfs in binaries, which are, of course, unknown. We can, however, show that the effect of dilution and averaging on the flux variations are normally not large without having a detailed knowledge of the mass and luminosity distributions. For dilution to reduce the flux variations by a large factor would require that the line strengths be peculiarly weak. Since none of the white dwarfs we observed had unusually weak lines, the maximum reduction for stars in our sample is unlikely to be greater than a factor of 2.

Equation (6) shows that velocity averaging has a large effect only if the luminosity ratio of the two stars is nearly the same as their mass ratio. The mass ratios of binary white dwarfs should lie between 0.5 and 2.0 (see the discussion in the next section). For velocity averaging to be important, the luminosities of the white dwarfs must also fall roughly within this same range. The luminosity of a white dwarf depends much more strongly on its age—and thus how long it has been cooling—than on its mass, and even small differences in age can produce large differences in luminosity. In the example given by Greenstein (1986), two identical DA white dwarfs with masses of 0.6 $M_\odot$ are formed only 6×10^8 yr apart and still have a luminosity difference of 0.9 mag after 2×10^9 yr. The stars in our survey are all bright white dwarfs and are almost certainly less than 2×10^9 yr old. Adopting a rough age of 10^9 yr and a luminosity difference of 1.2 mag, we find from equation (6) that the flux variations are reduced by a factor of 2. This example shows that exact cancelation of velocities is rare. Nevertheless, some cancelation must certainly occur. The example suggests that a factor of 2 is a reasonable limit to the reduction of the flux variations in all but the most exceptional cases.

In the following section we report the measured amplitudes of $\Delta F/F$ and the equivalent amplitudes of the radial velocities. The velocities are derived using equation (4) and do not include the effects of dilution and averaging. We do, however, include their effects when interpreting our results and we do so by degrading all the measured velocity limits by a uniform factor of 2.

The shortest period to which we were sensitive was typically 10 s in the original data but was increased to a uniform 30 s during the reduction procedure. The temperature of the filters was not controlled and drifted slowly during the night. The temperature drifts caused the central wavelengths of the filters to change and introduced systematic errors into the measured intensities. These systematic errors limited the length of the light curves to about 4 hr and, therefore, we were blind to periods longer than about 3 hr. We imposed uniformity on our results by truncating the period search at 3 hr. All the observations were made on the 2.7 m or 2.1 m telescopes at McDonald Observatory using the McDonald Observatory high-speed photometer and an RCA 8850 photomultiplier tube. Since the filters are narrow, the photon detection rates with this system were low, typically 100 counts s^{-1} for a DA4 white dwarf with $B = 14.0$ and 50 counts s^{-1} for a DB white dwarf of similar brightness. Signal averaging was, therefore, necessary to search for variability. For periods between 30 s and 45 minutes we calculated power spectra of the light curves; for periods between 45 minutes and 3 hr we averaged the data to 4 minute integrations and examined the resulting light curve directly.

III. RESULTS

a) The Space Density of Binary White Dwarfs

We chose white dwarfs from the McCook and Sion (1984) catalog of spectroscopically identified white dwarfs, avoiding known pulsating stars, stars with peculiar spectra, and stars with close visual companions. We observed 44 white dwarfs, of which four had DB spectral types and the rest had DA spectral types. The stars are listed in Table 3 with their spectral types, V magnitudes (the B magnitude for PG 0839+232, PG 0900+554, and G223–24), and the usable length of the light curve we obtained. We did not detect any binaries. Table 3 gives the upper limit to the semiamplitude of any periodicities in the light curves. We quote separate limits for the 30 s–45 minute period range and the 45 minute–3 hr period range. For the short-period range, the upper limits are the semiamplitudes of the largest peak in the power spectra of the light curves, and for the long period range the limits are one-half the maximum peak-to-peak excursions of the light curves. The limits in the 45 minute–3 hr period range are generally less stringent than for the 30 s–45 minute period range. The limits on the radial velocity variations calculated from equation (4) are also given in Table 3. The upper limit to the radial velocity variations is less than 70 km s^{-1} for 34 stars and between 70 and 100 km s^{-1} for the remaining 10 stars.

The velocity limits are good enough to have detected any short-period, binary white dwarfs in our sample. We show this by examining types of binary white dwarfs that would be unusually difficult to detect, and showing that we would have detected a large fraction of them. We calculate the fraction by adopting masses for the white dwarfs, amplitude limits for the radial velocity variations, and an orbital period. These yield an inclination above which the orbital inclination must lie if the white dwarf is to be detected and, therefore, the fraction of white dwarfs that will be detected. We assume that every binary has a period of 3 hr as this minimizes the orbital velocities of the binaries and maximizes the detection difficulty, and then we calculate two particularly awkward cases.

For the first case we assume that the white dwarfs have equal masses but we use *twice* the upper limits to the velocities given in Table 3 because the detection limit is degraded for binaries in which both stars contribute luminosity. Since the mass distribution of field white dwarfs is strongly peaked near 0.6 $M_\odot$ (Oke, Weidemann, and Koester 1984; Weidemann and Koester 1984), we use 0.6 $M_\odot$ for the mass of both stars (also see Iben and Tutukov 1986). For the 34 stars with an upper limit of 140 km s^{-1} (=twice 70 km s^{-1}) we would detect 80% of all binaries. For the 10 stars with an upper limit of 200 km s^{-1} (=twice 100 km s^{-1}) we would detect about 50% of all binaries.

For the second case we assume that the masses of the white dwarfs are unequal and that the white dwarf with the higher mass dominates the spectrum. We do not double the velocity limits because the two white dwarfs are likely to have greatly different luminosities. Since the mass ratio of binary white dwarfs is unlikely to be much smaller than 0.5 because of the narrow range of permissible white dwarf masses, we use 0.6 and 0.3 $M_\odot$ for the masses of the two stars (a system with 1.2 and 0.6 $M_\odot$ white dwarfs is not as difficult to detect). For the 34 stars with an upper limit of 70 km s^{-1} we would detect about 85% of all binaries. For the 10 stars with an upper limit of 100 km s^{-1} we would detect about 70% of all binaries.

Thus, although these are unusually difficult binaries to detect, we usually detect at least 70% of them and never detect less than about 50%. We believe, therefore, that we would have detected a large fraction—more than 90%—of all white dwarf binaries with orbital periods less than 3 hr.

Zero detections in 44 samples implies that the fraction of field white dwarfs that are short-period, binary white dwarfs is less than one in 20 with a probability of 0.9 and less than one in 37 with a probability of 0.7. The properties of the white dwarfs in our sample are roughly the same as the properties of the white dwarfs in the sample used by Fleming, Liebert, and Green (1986) to determine the space density and birth rates of all white dwarfs. We can scale their results to obtain limits on the space density of binary white dwarfs. According to Fleming *et al.* the space density of DA white dwarfs in the solar neighborhood with $M_V < 12.75$ is 4.9×10^{-4} pc^{-3}, and the ratio of

TABLE 3

NULL RESULTS FROM THE SURVEY FOR BINARY WHITE DWARFS

STAR					MAXIMUM SEMIAMPLITUDE (km s^{-1})			
					30 s–45 minutes		45 minutes–3 hr	
WD Number	Alias	Sp	V (mag)	LENGTH (hr)	$\Delta F/F$[a]	K	$\Delta F/F$[a]	K
WD 0002 + 729	GD 408	DB	14.34	4.10	9.1(−3)	41	1.1(−2)	50
WD 0004 + 330	GD 2	DA	13.82	3.99	3.7(−3)	16	4.8(−3)	21
WD 0100 − 068	G270–124	DB	13.95	3.99	2.0(−2)	89	1.9(−2)	80
WD 0148 + 467	GD 279	DA	12.44	3.99	4.0(−3)	17	1.2(−2)	52
WD 0227 + 050	Feige 22	DA	12.65	4.02	3.0(−3)	13	1.5(−2)	65
WD 0231 − 054	GD 31	DA	14.24	3.99	7.3(−3)	31	9.2(−3)	40
WD 0346 − 011	GD 50	DA	13.98	3.98	5.3(−3)	23	3.6(−3)	16
WD 0401 + 250	G8–8	DA	13.80	3.95	9.6(−3)	41	1.9(−2)	80
WD 0407 + 179	HZ 10	DA	14.14	4.20	1.4(−2)	60	8.0(−3)	34
WD 0410 + 117	HZ 2	DA	13.86	4.00	5.4(−3)	23	4.8(−3)	21
WD 0438 + 108	HZ 14	DA	13.83	3.96	6.5(−3)	28	2.0(−2)	86
WD 0453 + 418	GD 64	DA	13.77	3.92	1.1(−2)	47	1.5(−2)	65
WD 0501 + 527	G191–B2B	DA	11.78	3.98	1.3(−3)	6	4.7(−3)	20
WD 0549 + 158	GD 71	DA	13.06	3.88	3.2(−3)	14	9.1(−3)	39
WD 0612 + 177	G104–27	DA	13.40	4.93	3.2(−3)	14	1.4(−2)	60
WD 0644 + 375	G87–7	DA	12.10	5.05	1.9(−3)	8	9.0(−3)	39
WD 0713 + 584	GD 294	DA	12.0	4.06	1.9(−3)	8	1.1(−3)	5
WD 0839 + 232	PG 0839 + 232	DA	14.18B	4.00	5.1(−3)	22	1.1(−2)	52
WD 0900 + 554	PG 0900 + 554	DA	13.83B	4.02	3.7(−3)	16	9.8(−3)	42
WD 0943 + 441	G116–52	DA	13.25	4.01	5.0(−3)	22	1.8(−2)	78
WD 1104 + 602	G197–4	DA	13.80	4.24	9.5(−3)	41	1.3(−2)	56
WD 1105 − 048	G163–50	DA	12.92	3.75	3.7(−3)	16	2.7(−3)	12
WD 1134 + 300	GD 140	DA	12.55	3.95	2.6(−3)	11	3.7(−3)	16
WD 1143 + 321	G148–7	DA	13.65	3.57	7.6(−3)	33	2.1(−2)	91
WD 1232 + 479	GD 148	DA	14.52	4.03	6.1(−3)	26	1.1(−2)	47
WD 1254 + 223	GD 153	DA	13.42	4.06	2.8(−3)	12	1.2(−2)	52
WD 1317 + 453	G177–31	DA	14.13	4.00	4.7(−3)	20	5.6(−3)	24
WD 1337 + 705	G238–44	DA	12.79	3.72	2.7(−3)	12	3.3(−3)	14
WD 1344 + 572	G223–24	DA	12.95B	4.16	3.5(−3)	15	6.2(−3)	27
WD 1408 + 323	GD 163	DA	13.97	4.08	4.6(−3)	20	5.0(−3)	22
WD 1509 + 322	GD 178	DA	14.11	4.58	9.2(−3)	40	1.9(−2)	82
WD 1713 + 322	GD 360	DA	14.46	4.02	7.0(−3)	30	3.5(−3)	15
WD 1713 + 695	G240–51	DA	13.29	3.68	7.8(−3)	34	1.8(−2)	78
WD 1822 + 410	GD 378	DB	14.39	5.02	2.1(−2)	94	2.2(−2)	98
WD 1824 + 040	G21–15	DA	13.90	4.01	6.8(−3)	29	1.3(−2)	56
WD 1919 + 145	GD 219	DA	12.97	4.05	4.9(−3)	21	1.2(−2)	52
WD 1940 + 374	L1573–31	DB	14.51	6.64	9.8(−3)	41	1.5(−2)	67
WD 2032 + 248	G186–31	DA	11.53	4.59	2.0(−3)	9	3.1(−3)	13
WD 2136 + 828	G261–45	DA	13.02	3.95	5.2(−3)	22	9.5(−3)	41
WD 2149 + 021	G93–48	DA	12.75	3.83	6.6(−3)	28	1.9(−2)	80
WD 2256 + 249	GD 245	DA	13.63	4.01	4.5(−3)	19	2.3(−2)	99
WD 2309 + 105	GD 246	DA	13.05	3.90	3.9(−3)	17	1.1(−2)	47
WD 2329 + 407	G171–2	DA	13.82	3.19	9.6(−3)	41	1.4(−2)	60
WD 2341 + 322	G130–5	DA	12.90	3.94	5.5(−3)	24	7.9(−3)	34

[a] Numbers in parentheses represent powers of 10; e.g., 1.1(−2) means 1.1×10^{-2}, etc.

DA to non–DA white dwarfs is (4.3 ± 0.7) to 1. Therefore, the space density of short-period, binary white dwarfs of all spectral types brighter than $M_V = 12.75$ is less than 3.0×10^{-5} pc^{-3} with a probability of 0.9 and it is less than 1.6×10^{-5} pc^{-3} with a probability of 0.7.

b) *Implications*

There are several implications of our results. First, the low space density of binary white dwarfs presents difficulties for models of Type I supernovae in which the supernovae are caused by the merging of a pair of white dwarfs. We will show this by assuming that these models are correct, working backward from the observed rate of Type I supernovae in the galaxy to the required space density of progenitor binary white dwarfs, and showing that the required space density of progenitors is higher than the observed space density.

If the distribution of binary white dwarfs is in a steady state, the period distribution for binary white dwarfs that will merge to form Type I supernovae is given by

$$n(P) = R\left(\frac{dP}{dt}\right)^{-1}, \tag{7}$$

where $n(P)$ is the space density of binary white dwarfs that will become Type I supernovae, R is the local rate of Type I supernovae in our galaxy, and dP/dt is the rate of change of the periods of the binaries. We assume that the only mechanism causing the orbits to decay is gravitational radiation. The equation for the rate of change of the period is, then,

$$\frac{dP}{dt} = \frac{-96(2\pi)^{8/3}G^{5/3}}{5c^5}\frac{M_1 M_2}{(M_1 + M_2)^{1/3}}P^{-5/3}, \tag{8}$$

where the symbols have their usual meanings (Faulkner 1971). Combining equations (7) and (8), we have

$$n(P) = 8.58 \times 10^{60} R \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P^{5/3} , \qquad (9)$$

where P is in seconds and the masses are in grams. The required space density of binaries with orbital periods less than some maximum period, $P_{\max}$, is given by

$$N = \int_0^{P_{\max}} n(P)dP = 3.22 \times 10^{60} R \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P_{\max}{}^{8/3} . \qquad (10)$$

According to Tammann (1982), the local rate of Type I supernovae in the Galaxy is $R = 6.8 \times 10^{-14}$ pc^{-3} yr^{-1} = 2.15×10^{-21} pc^{-3} s^{-1} with an error possibly as large as 50%[1]. Since equation (10) will give the minimum required space density of progenitor binaries if the white dwarfs have equal masses and if their masses are high, we adopt a mass of 0.7 $M_\odot$ for both white dwarfs. Using $P_{\max} = 10{,}800$ s, we find $N = 2.8 \times 10^{-5}$ pc^{-3}.

Thus, the *minimum* space density of binary white dwarfs required to produce the observed rate of Type I supernovae is 2.8×10^{-5} pc^{-3}. This minimum density is greater than or equal to the observed limit on the space density. Only if *every* binary white dwarf becomes a Type I supernova could the required space density be consistent with the observed limit on the space density. This is impossible because most binaries will not have enough total mass to be candidates for Type I supernovae. We conclude, therefore, that binary white dwarfs are not the dominant progenitors of Type I supernovae.

There is one important loophole in our discussion. White dwarf binaries could still be the progenitors of Type I supernovae if they first form with extremely short orbital periods or extremely long orbital periods. If they are all created with orbital periods less than 10 or 20 minutes, their orbital periods would decrease on time scales of only a few million years because of gravitational radiation. As shown by equation (7), the space density of these short-lived binaries could be low, much lower than the observed limit on the space density, and still be high enough to account for all Type I supernovae. If the orbital periods start off longer than roughly 5 hr, the orbits would take so long to decay that the white dwarfs would cool to low temperatures by the time they reach orbital periods to which we were sensitive. They might then be too faint to observe, their spectral types might no longer be DA or DB, and they would be missed by our survey.

We cannot conclusively eliminate this loophole but there is evidence against it. Trimble (1985) has examined the radial velocities of all white dwarfs for which two or more velocities have been published and found only six white dwarfs with discrepant velocities. We observed two of the three DA white dwarfs on her list (the rest were DO white dwarfs or were in the southern hemisphere) and did not find any variability in their velocities; the third DA white dwarf, HL Tau 76, is a pulsating white dwarf (Landolt 1968) and the reported variations in its radial velocity were spurious. Trimble's survey was sensitive to binaries with longer orbital periods than ours. The failure to find any confirmed binaries in her sample suggests that there is not a large population of white dwarf binaries with periods longer than 3 hr. The example of LB 3459, which has an orbital period of 6.3 hr and is the only demonstrable progenitor of a binary white dwarf, shows that not all binary white dwarfs are formed at extremely short orbital periods (Kilkenny, Hill, and Penfold 1981). One of the few binaries demonstrably descendant from a common envelope binary is the central star of Abell 41 (Grauer and Bond 1983). Although it is not destined to become a binary white dwarf soon—or possibly ever (one component is a dM star), the physical mechanisms at work during the formation of Abell 41 were similar to those at work during the formation of binary white dwarfs. Its 2.7 hr orbital period shows that not all common envelope binaries are formed with extremely short orbital periods. Finally, theoretical estimates of the initial periods of binary white dwarfs suggest that they are formed at all orbital periods between roughly 15 minutes and somewhat over a day (Webbink 1984). Thus, although we cannot close the loophole completely, we conclude that it is unlikely that binary white dwarfs are all or even predominantly formed at extremely long or extremely short orbital periods.

Our results also bear on theoretical estimates of the birth rates of close binary stars. Estimates of the birth rates and space densities of binary stars in the late stages of their evolution are extremely uncertain, primarily because of uncertainties in the physical processes at work during common envelope stages of their evolution. We note for example that recent theoretical estimates of the birth rates of CO + CO binary white dwarfs differ by as much as a factor of 10, Tornambè and Matteucci (1986) finding a rate lower by an order of magnitude than Iben and Tutukov (1984) found. The observed limit on the space density and birth rates of binary white dwarfs suggest that the lower estimate is more nearly correct.

Finally, our results have implications for the design of gravitational wave detectors. The dominant source of the gravitational wave background radiation at periods between about 30 s and 1 hr should be binary white dwarfs (Douglass and Braginsky 1979; Clark and Epstein 1979). This background limits the sensitivity of gravitational wave detectors at these periods because it acts like a background noise against which signals must be detected. Space experiments sensitive to gravitational waves at these periods have been proposed (e.g., Faller *et al.* 1985) and should be sensitive enough to detect the background gravitational radiation. Their sensitivity is, therefore, set by the space density of binary white dwarfs. The most recent estimates of the gravitational wave background have been based on the higher theoretical estimates of the birth rates of binary white dwarfs (Webbink 1984) and indicated that the background should limit the sensitivity at periods between 30 and 3000 s (e.g., Hils *et al.* 1986). Our results show that the space density of binary white dwarfs is much lower and that the experiments should be detector-limited in this period range.

To summarize, the fraction of white dwarfs that are short-period binaries is less than one in 20 with a probability of 0.9 and less than one in 37 with a probability of 0.7. The upper limit on the space density of binary white dwarfs brighter than $M_V = 12.75$ is 3.0×10^{-5} pc^{-3} with a probability of 0.9 and 1.6×10^{-5} pc^{-3} with a probability of 0.7. It is unlikely,

[1] The redetermination of the supernova rate in the Shapley-Ames galaxies by van den Bergh, McClure, and Evans (1988) shows that the supernova rates for bright galaxies given by Tammann (1982) should be reduced by a factor of 3. The reduction does not, however, apply to the rate of supernovae in our own galaxy as this rate is based on local observations. See van den Bergh (1983, 1987) for fuller discussions.

although not impossible, that there is a large population of binary white dwarfs that our survey would fail to detect, and, therefore, it is unlikely that these limits can be relaxed by a large factor. This space density is too low to account for the rate of Type I supernovae in the Galaxy. It also agrees better with lower rather than with higher theoretical estimates of the birth rates of binary white dwarfs. The space density is low enough that the sensitivity of space experiments for detecting gravitational wave events should be limited by instrumental sensitivity rather than the gravitational wave background at periods between 30 and 3000 s.

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