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Short gamma-ray bursts in old populations: magnetars from white dwarf–white dwarf mergers

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ABSTRACT

Recent progress on the nature of short-duration gamma-ray bursts has shown that a fraction of them originate in the local Universe. These systems may well be the result of giant flares from soft gamma-repeaters (highly magnetized neutron stars commonly known as magnetars). However, if these neutron stars are formed via the core collapse of massive stars then it would be expected that the bursts should originate from predominantly young stellar populations, while correlating the positions of BATSE short bursts with structure in the local Universe reveals a correlation with all galaxy types, including those with little or no ongoing star formation. This is a natural outcome if, in addition to magnetars formed via the core collapse of massive stars, they also form via accretion-induced collapse following the merger of two white dwarfs, one of which is magnetic. We investigate this possibility and find that the rate of magnetar production via white dwarf–white dwarf (WD–WD) mergers in the Milky Way is comparable to the rate of production via core collapse. However, while the rate of production of magnetars by core collapse is proportional to the star formation rate, the rate of production via WD–WD mergers (which have long lifetimes) is proportional to the stellar mass density, which is concentrated in early-type systems. Therefore magnetars produced via WD–WD mergers may produce soft gamma-repeater giant flares which can be identified with early-type galaxies. We also comment on the possibility that this mechanism could produce a fraction of the observed short-duration burst population at higher redshift.

Key words: white dwarfs – gamma-rays: bursts.

1 INTRODUCTION

Soft gamma-repeaters (SGRs) are thought to be highly magnetized neutron stars with rotational periods of seconds and strong ($>10^{14}$ G) magnetic fields (Duncan & Thompson 1992; Kouveliotou et al. 1998). They undergo frequent outbursts and occasional giant flares (Hurley et al. 1999; Palmer et al. 2005). These giant flares are sufficiently bright to be observed in external galaxies out to large distances ($>$50 Mpc), and would be observable as a short-duration gamma-ray burst (GRB) (Hurley et al. 2005). However, the paucity of observed giant flares in our own Galaxy has so far precluded observationally based determinations of either their luminosity function or their rate.

Observations of recently localized short-duration GRBs have shown them to be associated with a variety of host galaxy types at typical redshifts of $z \sim 0.2$ (e.g. Gehrels et al. 2005; Fox et al. 2005; Berger et al. 2005). Their energetics, and location in a variety of host galaxies, including those with little or no ongoing star formation, point to an origin in the merger of two compact objects, either neutron star–neutron star or neutron star–black hole (Bloom et al. 2005; Hjorth et al. 2005).

However, if at least some fraction of short-duration GRBs are due to SGRs in external galaxies, then it may be expected that some correlation between the positions of bursts and the locations of galaxies in the local Universe would be seen. Tanvir et al. (2005, hereafter T05) have recently reported such a correlation, indicating that up to $\sim$25 per cent of short-duration GRBs originate in the local Universe (within 100 Mpc). Intriguingly, this analysis shows a correlation with all galaxy types, and is strongest when restricted to relatively early-type galaxies (Sbc and earlier). SGRs are thought to be formed in the core collapse of massive stars, and because of relatively short lifetimes ($\sim10^4$ yr, e.g. Kouveliotou 1999) would naturally be located in predominantly star-forming galaxies, while essentially none should be seen in ellipticals. Two possibilities present themselves: the first is that, rather than representing SGRs, the correlations

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reported by T05 are due to a different progenitor class, such as low-luminosity neutron star mergers. The second possibility is that SGRs are not created exclusively by core-collapse events and can be found in older stellar populations. This second option is the subject of this Letter.

Here we consider an alternative model for the creation of SGRs, and thus potentially GRBs: namely SGRs that are created via the accretion-induced collapse (AIC) of white dwarfs to neutron stars (e.g. Nomoto & Kondo 1991). Such an AIC may occur in white dwarf–white dwarf (WD–WD) mergers (Usov 1992; King, Pringle & Wickramasinghe 2001), or rarely in binaries with more massive main-sequence companions although the precise outcome of WD–WD mergers remains uncertain, and may produce either a type Ia supernova (SN Ia) or an AIC. Once the magnetar has been created, its evolution will proceed in an analogous manner to those created via core collapse.

2 MAKING MAGNETARS FROM WHITE DWARF MERGERS

King et al. (2001) first suggested that the merger of two white dwarfs (one or more of which was highly magnetic) may result in the production of a magnetar via AIC. Observational evidence for such a channel can be found from the highly magnetic white dwarf RE J0317−853, which appears to be the result of the merger of two white dwarfs with a total mass marginally below the Chandrasekhar limit. For more massive systems a magnetar may be formed.

However, the required field strengths for the white dwarfs are very large. Upon collapse the new magnetic field is given by $B_{\rm NS} = B_{\rm WD}(R_{\rm WD}/R_{\rm NS})^2$. For typical white dwarf and neutron star parameters this implies that white dwarf B-fields of several hundred MG are necessary for magnetar creation. Such fields are relatively rare, but do exist within the magnetic white dwarf population. Fig. 1 shows the distribution of magnetic fields in isolated white dwarfs and in magnetic cataclysmic variables (Wickramasinghe & Ferrario 2000; Schmidt et al. 2003; Norton, Wynn & Somerscales 2004; Vanlandingham et al. 2005). As can be seen, a small fraction (∼10 per cent) achieve the required field strengths. This may be considered a lower limit as magnetars may also be formed from stars with lower fields via post-collapse dynamos (e.g. Thompson & Duncan 1995). Thus it is plausible that the AIC of a white dwarf during the merging process could create a magnetar.

3 THE RATE OF FORMATION OF MAGNETARS FROM WD–WD MERGERS

We now proceed to estimate roughly the rate of formation of SGRs via the WD–WD channel within the Milky Way. Initially we construct a mass distribution containing both magnetic and non-magnetic carbon–oxygen (CO) white dwarfs (Fig. 2). The mass function for the non-magnetic systems is taken from Liebert, Bergeron & Holberg (2005), exhibiting a broad structure with a peak at ∼0.57 $M_\odot$. The mass function for highly magnetic white dwarfs is markedly different from this, and for this work is considered to be flat between 0.5 and 1.4 $M_\odot$ with a mean of 0.95 $M_\odot$ (this is consistent with current observations of magnetic white dwarfs: Liebert, Bergeron & Holberg 2003; Nalezyty & Madej 2004). The fraction of magnetic white dwarfs (with $B > 2$ MG) within this model is 9 per cent, again consistent with recent observations (e.g. Liebert et al. 2003). For each white dwarf we obtain a radius using the formulation of Nauenberg (1972), and, for magnetic white dwarfs calculate the B-field that would be formed upon collapse to a neutron star of radius 1×10^6 cm. We only consider CO white dwarfs

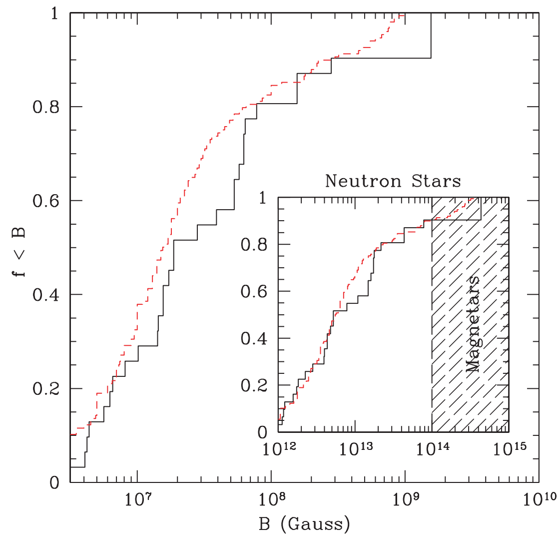

Figure 1. The distribution of white dwarf magnetic fields seen in magnetic cataclysmic variables [black line – 33 stars taken from Norton et al. (2004)] and isolated white dwarfs [red dashed line – 148 stars with $B > 2$ MG, taken from Wickramasinghe & Ferrario (2000), Schmidt et al. (2003) and Vanlandingham et al. (2005)]. For magnetic cataclysmic variables we have converted from magnetic moment to B-field assuming that $R = 6 \times 10^8$ cm [the radius of a mean-mass (0.95 $M_\odot$) magnetic white dwarf]. A more detailed description including the effects of the white dwarf mass–radius relation is given in Section 3. The inset shows the fields following collapse into a neutron star of radius 1×10^6 cm. Magnetars are defined as having $B > 10^{14}$ G.

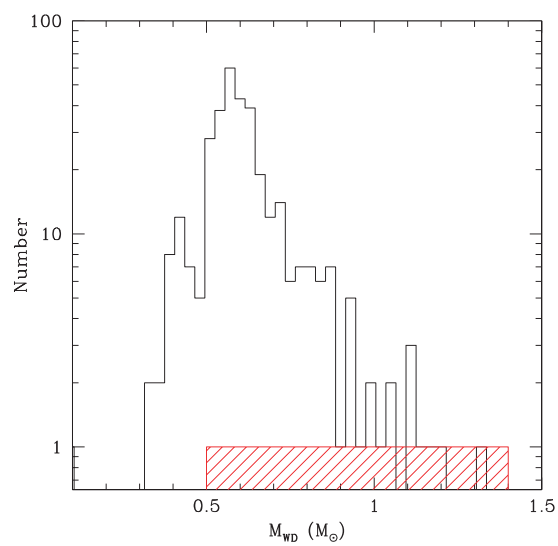

Figure 2. The mass distributions assumed for this work. The non-magnetic white dwarf distribution has been taken from Liebert et al. (2005), while the magnetic distribution is assumed to be flat over the mass range of $0.5 < M < 1.4$ $M_\odot$, as is shown in the hatched area. The relative numbers of white dwarfs in each population are those assumed here.

since although He–He systems are the dominant double-degenerate population by number, they are of less interest as sources of magnetars, since they will rarely exceed the Chandrasekhar mass. Detailed population synthesis calculations by Nelemans et al. (2001) find that ∼25 per cent of the WD–WD systems formed consist of two CO white dwarfs.

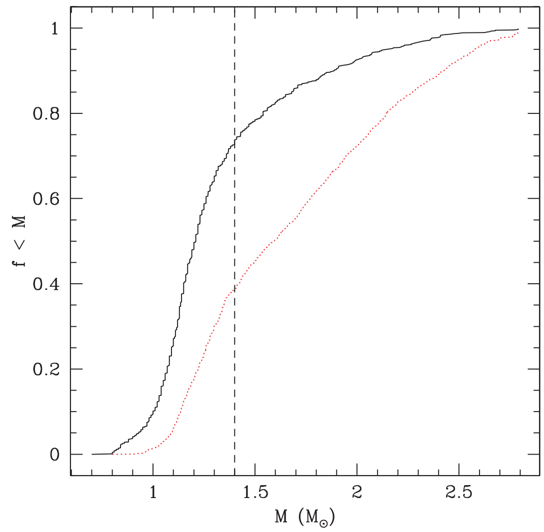

Figure 3. The distribution of the combined masses of mergers of CO white dwarfs, where each component is picked to favour mass ratios close to unity as described in Section 3. The red dotted line shows the mass distribution of double-degenerate systems that contain a magnetic white dwarf. As can be seen, it is charaterized by a higher mean mass, due to the differing shape of the magnetic white dwarf mass function. The dashed vertical line represents the Chandrasekhar mass.

We do not consider the detailed evolutionary pathways that lead to the production of the WD–WD binaries, but do pick white dwarfs from the mass distribution such that the observed mass ratios are consistent with observations (Maxted, Marsh & Moran 2002). To this end we pick the first white dwarf at random from the entire mass distribution but then pick the secondary from a Gaussian function, centred on the mass of the first WD with a FWHM of 20 per cent of this mass. This preferentially produces binaries with mass ratios close to unity, in agreement with observations of double-degenerate systems.

We find that the fraction of double-degenerate systems that form above the Chandrasekhar mass is ~25 per cent of our population (or ~6 per cent of the total WD–WD population if CO–He and He–He systems are also considered). As we do not attempt detailed population synthesis calculations here, we instead normalize the double degenerates created with masses $> 1.4\ \mathrm{M}_\odot$ against the rate obtained via population synthesis (Nelemans et al. 2001), so that the rate of such mergers is $3 \times 10^{-3}\ \mathrm{yr}^{-1}$. Of this population, ~40 per cent contain at least one magnetic white dwarf. Although this appears to be a larger fraction than might naturally be anticipated, it is due to the fact that magnetic white dwarfs exhibit a higher mean mass, so that the distribution of WD–WD binaries containing a magnetic white dwarf is biased towards higher masses (see Fig. 3 – at masses above ~1 $\mathrm{M}_\odot$ the mass function of magnetic white dwarfs contributes approximately the same number of stars as the non-magnetic population). In approximately 10 per cent of the double-degenerate systems (with $M > 1.4\,\mathrm{M}_\odot$) the magnetic fields are sufficiently strong to form a magnetar should an AIC occur upon merger.

4 DISCUSSION

The currently popular picture for the production of magnetars is that they result from the core collapse of stars more massive than 40 $\mathrm{M}_\odot$ (e.g. Gaensler et al. 2005). The rate of production of such stars within the Galaxy is $\sim 6 \times 10^{-4}\ \mathrm{yr}^{-1}$ (Podsiadlowski et al. 2004). The rate of SGRs (created by both WD–WD and core-collapse channels) can also be estimated based on the observed number within our Galaxy. Given a lifetime of 10^4 yr and the observed number within the Milky Way (four), the estimated rate is $\sim 4 \times 10^{-4}\ \mathrm{yr}^{-1}$. The location of the observed Galactic SGRs within the Galactic plane and the association in some cases with young stellar clusters make it reasonable to assume that all of the Galactic SGRs have been created via core collapse, although this is not certain. The total rate is also a lower limit since it is possible that some Galactic SGRs have been quiescent and have thus far evaded detection.

Nelemans et al. (2001) estimate a rate of mergers of white dwarf binaries with masses higher than the Chandrasekhar mass of $3 \times 10^{-3}\ \mathrm{yr}^{-1}$. Thus if ~10 per cent of these systems create a magnetar then we expect a Galactic rate of magnetar production via WD–WD mergers of $3 \times 10^{-4}\ \mathrm{yr}^{-1}$. This this is comparable to the rate inferred from core collapse.

The rate of core-collapse events within the local Universe should trace the massive star formation rate (SFR), while the rate of SGRs formed via WD–WD mergers will better trace the stellar mass density, since the merger of the white dwarf pair can occur several Gyr after the star formation that created the white dwarf progenitors. In early-type systems the rate of production of SGRs via WD–WD mergers will be significantly larger than via core collapse. For example, in an early-type galaxy, the SFR may be $\sim 0.1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$, while the stellar mass may be similar to the Milky Way. In such systems the rate of production via core collapse would be $\sim 1 \times 10^{-5}\ \mathrm{yr}^{-1}$, while the rate of production via WD–WD mergers would be unchanged at $\sim 3 \times 10^{-4}\ \mathrm{yr}^{-1}$, a factor of 10 higher than the core-collapse rate.

Given the SFR and stellar mass of the Milky Way [following the calculations of Nelemans et al. (2001), we assume SFR $= 4\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ and $M_{\mathrm{disc}} = 8 \times 10^{10}\ \mathrm{M}_\odot$], we estimate the rate of production by WD–WD mergers and by core-collapse events to be $\Re_{\mathrm{WD-WD}} \approx 3.5 \times 10^{-4}\ \mathrm{yr}^{-1} \times (M/10^{11}\ \mathrm{M}_\odot)$ and $\Re_{\mathrm{CC}} \approx 1 \times 10^{-4}\ \mathrm{yr}^{-1} \times [\mathrm{SFR}/(\mathrm{M}_\odot\ \mathrm{yr}^{-1})]$. An extrapolation of this to the local Universe is shown in Fig. 4. The rates of SGR production via core collapse and WD–WD mergers are comparable within the uncertainties. Thus SGRs produced via WD–WD mergers would naturally predict a correlation between the locations of short GRBs and galaxies of all types in the local Universe. Indeed, the total rate of SGR production in earlier type galaxies (T-type 4 and earlier, where T05 find their strongest correlation) is predicted to be $\sim 0.2\ \mathrm{yr}^{-1}$, or 70 per cent of the total SGR production, providing a natural explanation of this result. Some enhancement of the rate of WD–WD mergers may also be seen in globular clusters where the systems can be formed dynamically as well as via the normal binary evolution channels. Although this enhancement is probably only modest (see e.g. Davies & Benz 1995), it would primarily act to enhance the rate of mergers in very early-type systems, where a large number of globular clusters are found.

The predicted total rate of $\sim 0.3\ \mathrm{yr}^{-1}$ combined with the lifetime of SGRs of 1×10^4 yr implies that within a velocity cut of $<2000\ \mathrm{km\ s}^{-1}$ there exist ~3000 SGRs. The results of T05 indicate that ~3 short GRBs per year occur within this volume. If this is the case then it implies that the rate of SGR giant flares is approximately one per SGR every 1000 yr (i.e. within the Milky Way where there are four SGRs, a giant flare of the magnitude of that seen from SGR 1806−20 in 2004 December would be expected every 250 yr). This is not unreasonable, since it is thought that giant flares similar to that seen in SGR 1806−20 might release ~10 per cent of the magnetar

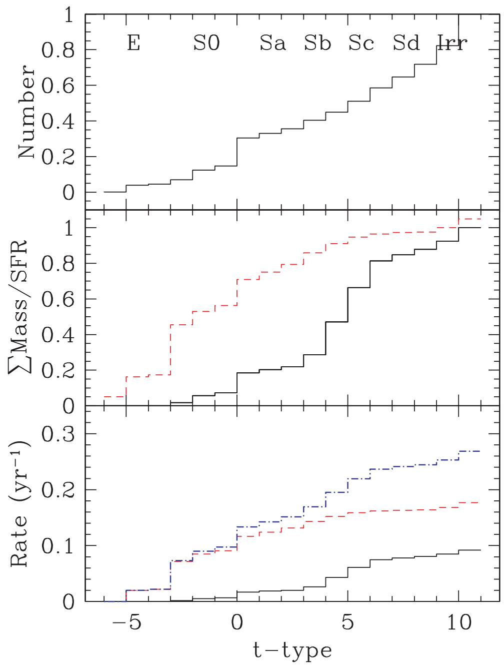

Figure 4. Top: the distribution of different T-types within the Third Reference Catalogue of Bright Galaxies (RC3 – de Vaucouleurs et al. 1995) with $v < 2000$ km s^{-1}. The T-type distribution runs along the Hubble sequence between −6 (elliptical) and 11 (irregular); the Hubble type for a given T-type is indicated in the top panel. Middle: the cumulative distribution of stellar mass (red dashed) and star formation (black solid) within the same velocity cut; the model for stellar mass and star formation assumed to create this is described in Appendix A. As can be seen, much of the stellar mass is maintained in early-type systems, while star formation takes place predominantly in later systems. The lower panel shows the extrapolated rates of SGRs which follow (red dashed line) the stellar mass at a rate of 3.5×10^{-4} yr^{-1} $\times$ ($M/10^{11}$ M$_{\odot}$) and follow (solid black line) the star formation rate as 1×10^{-4} yr^{-1} $\times$ (SFR/M$_{\odot}$ yr^{-1}). Within the considerable uncertainties, the rates of each channel within the local Universe are comparable and thus we may expect to see a correlation between the locations of short bursts and all galaxy types. The blue dot–dashed line shows the cumulative rate of SGR formation via both channels. As can be seen, the rate of formation in earlier type galaxies (T-type 4 and earlier) accounts for ∼ 70 per cent of the total rate.

dipole energy, therefore this rate fits well with the estimated lifetime of SGRs of 10^4 yr.

It is interesting to note that a primary piece of evidence used to argue that the recently located short-burst population is the result of compact binary (neutron star or black hole) mergers is the association of short GRBs with all galaxy types, *including* those with little or no ongoing star formation. This immediately rules out any connection with events requiring ongoing star formation. Under the standard assumption that SGRs are produced via core collapse, this observation can also be used to argue that SGRs cannot be responsible for the recent well-localized short-duration bursts. However, it should be noted that under our proposed model we would expect to locate bursts in all galaxy types. Indeed, the galaxy type fractions for WD–WD mergers may be similar to those of SNe Ia, or may even be biased to typically earlier type galaxies if the SN Ia population is represented by two progenitor classes [one of which is enhanced in younger populations (e.g. Mannucci, Della Valle & Panagia 2005b)]. Given the long lifetimes of the WD–WD dwarf systems, we would not expect to find them in or near regions of massive star formation, and in this sense their locations in host galaxies may be similar to those of neutron star–neutron star mergers. However, the dynamics of their formation will differ from neutron star–neutron star and neutron star–black hole binaries (in the sense that WD–WD systems will not have natal kicks as neutron stars do), and so the location of bursts around their hosts may enable the distinction between different models.

There are limits to the energetics that can feasibly be achieved via SGR giant flares. Those observed within the Milky Way have achieved luminosities up to 10^{46} erg, although Hurley et al. (2005) comment that it may be possible to achieve luminosities a factor of 100 greater. None the less, the most luminous short-duration bursts with energies of 10^{50} erg would appear to be beyond the energies that can be created via SGRs, implying that two populations of bursts are still required. Ultimately observations of SGRs in nearby galaxies may enable the determination of their luminosity function and fix the rate at which they occur.

5 CONCLUSIONS

We have presented a mechanism for the production of magnetars via AIC following the merger of two white dwarfs in a tight binary. Considering the observed mass and magnetic field distributions for white dwarfs, it appears that the rate of formation of SGRs via this process in the local Universe is comparable to the production rate via the core-collapse channel (although possibly slightly lower than the core-collapse channel in the Milky Way). In early-type galaxies the WD–WD mechanism is the dominant producer of SGRs, while in late-type galaxies most SGRs are produced via core collapse. Thus it would be expected that SGR flares appearing as short-duration GRBs may be found from galaxies of all types, and this naturally explains the correlation seen between the locations of BATSE short-duration bursts and early-type galaxies in the local Universe.

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REFERENCES

Berger E. et al., 2005, Nat, 438, 988
Bloom J. S. et al., 2005, preprint (astro-ph/0505480)
Davies M. B., Benz W., 1995, MNRAS, 276, 876
de Vaucouleurs G., de Vaucouleurs A., Corwin H. G., Buta R. J., Paturel G., Fouque P., 1995, VizieR Online Data Catalog, 7155, 0. Available online: http://vizier.u-strasbg.fr/viz-bin/Cat?VII/155
Duncan R. C., Thompson C., 1992, ApJ, 392, 9
Fox D. B. et al., 2005, Nat, 437, 845
Gaensler B. M., McClure-Griffiths N. M., Oey M. S., Haverkorn M., Dickey J. M., Green A. J., 2005, ApJ, 620, L95
Gallego J., Zamorano J., Aragon-Salamanca A., Rego M., 1995, ApJ, 455, L1

Gehrels N. et al., 2005, Nat, 437, 851
Hjorth J. et al., 2005, ApJ, 630, L117
Hurley K. et al., 1999, Nat, 397, 41
Hurley K. et al., 2005, Nat, 434, 1098
King A. R., Pringle J. E., Wickramasinghe D. T., 2001, MNRAS, 320, L45
Kouveliotou C., 1999, Proc. Natl Acad. Sci., 96, 5351
Kouveliotou C. et al., 1998, Nat, 393, 235
Liebert J., Bergeron P., Holberg J. B., 2003, AJ, 125, 348
Liebert J., Bergeron P., Holberg J. B., 2005, ApJS, 156, 47
Mannucci F., della Valle M., Panagia N., Cappellaro E., Cresci G., Maiolino R., Petrosian A., Turatto M., 2005a, A&A, 433, 807
Mannucci F., Della Valle M., Panagia N., 2005b, preprint (astro-ph/0510315)
Maxted P. F. L., Marsh T. R., Moran C. K. J., 2002, MNRAS, 332, 745
Nalezyty M., Madej J., 2004, A&A, 420, 507
Nauenberg M., 1972, ApJ, 175, 417
Nelemans G., Yungelson L. R., Portegies Zwart S. F., Verbunt F., 2001, A&A, 365, 491
Nomoto K., Kondo Y., 1991, ApJ, 367, L19
Norton A. J., Wynn G. A., Somerscales R. V., 2004, ApJ, 614, 349
Palmer D. M. et al., 2005, Nat, 434, 1107
Podsiadlowski P., Mazzali P. A., Nomoto K., Lazzati D., Cappellaro E., 2004, ApJ, 607, L17
Schmidt G. D. et al., 2003, ApJ, 595, 1101
Shane N. S., James P. A., 2002, in Athanassoula E., Bosma A., Mujica R., eds, ASP Conf. Ser. Vol. 275, Disks of Galaxies: Kinematics, Dynamics and Peturbations. Astron. Soc. Pac., San Francisco, p. 323
Tanvir N., Chapman R., Levan A., Priddey R., 2005, Nat, 438, 991 (T05)
Usov V. V., 1992, Nat, 357, 472
Vanlandingham K. M. et al., 2005, AJ, 130, 734
Wickramasinghe D. T., Ferrario L., 2000, PASP, 112, 873

APPENDIX A: MASS AND STAR FORMATION IN THE LOCAL UNIVERSE

In order to estimate the rate of SGR production within different galaxy types in the local Universe, we have created a crude model which estimates the star formation and mass of galaxies within the Third Reference Catalogue of Bright Galaxies, RC3 (de Vaucouleurs et al. 1995).

We initially cut the RC3 catalogue including only galaxies with $v < 2000$ km s^{-1}, roughly 28 Mpc. We then cross-correlate the positions of these galaxies with the Two-Micron All-Sky Survey (2MASS) extended source catalogue to obtain $B - K$ colours for each of the galaxies. We are then able to estimate the mass of each individual galaxy using the relation given by Mannucci et al. (2005a):

$$\log\left(\frac{M/L_K}{\mathrm{M}_\odot/\mathrm{L}_\odot}\right) = 0.212(B - K) - 0.959. \quad \text{(A1)}$$

Having ascertained the mass, we now derive rough estimates for the star formation contained within each galaxy T-type. We estimate this based on the mean SFR of galaxies of a given T-type (from Shane & James 2002). The rates that we assume are E ($0\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), S0 ($0.2\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), Sa ($0.25\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), Sb ($0.5\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), Sc ($1.4\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), Scd ($1.1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$), Sd ($0.7\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$) and Irr ($0.15\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$). While these numbers only crudely estimate the SFR for a given galaxy, the total SFR obtained via this assumption is in agreement with the extrapolation of the local SFR to $v < 2000$ km s^{-1} (Gallego et al. 1995).

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