Mon. Not. R. Astron. Soc. **370,** L14–L18 (2006) doi:10.1111/j.1745-3933.2006.00178.x

Supernova remnant energetics and magnetars: no evidence in favour of millisecond proto-neutron stars

Jacco Vink[1,2]★ and Lucien Kuiper[2]

[1] *Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA Utrecht, the Netherlands*
[2] *SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584CA Utrecht, the Netherlands*

Accepted 2006 April 7. Received 2006 April 7; in original form 2005 December 15

ABSTRACT

It is generally accepted that anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are magnetars, i.e. neutron stars with extremely high surface magnetic fields ($B > 10^{14}$ G). The origin of these high magnetic fields is uncertain, but a popular hypothesis is that magnetars are born with an initial spin period not much exceeding the convective overturn time (∼3 ms), which results in a powerful dynamo action, amplifying the seed magnetic field to $\gtrsim 10^{15}$ G. Part of this rotation energy is then expected to power the supernova through rapid magnetic braking. It is therefore possible that magnetar creation is accompanied by supernovae that are an order of magnitude more energetic than normal supernovae, provided their initial spin period is ∼1 ms. However, we list here evidence that the explosion energies of these supernova remnants associated with AXPs and SGRs – Kes 73 (AXP 1E 1841−045), CTB 109 (AXP 1E2259+586) and N49 (SGR 0526−66) – are close to the canonical supernova explosion energy of 10^{51} erg, suggesting an initial spin period of $P_0 \gtrsim 5$ ms.

We therefore do not find evidence that magnetars are formed from rapidly rotating proto-neutron stars, allowing for the possibility that they descend from stellar progenitors with high magnetic field cores, and discuss the merits of both formation scenarios.

In an appendix we describe the analysis of *XMM–Newton* observations of Kes 73 and N49 used to derive the explosion energies for these remnants.

Key words: stars: magnetic fields – stars: neutron – ISM: supernova remnants – ISM: individual: N49 – ISM: individual: Kes 73 – ISM: individual: CTB 109.

1 INTRODUCTION

The notion that neutron stars exist with surface magnetic fields as high as 10^{14}–10^{15} G has become generally accepted over the last decade. The most spectacular manifestations of these so-called magnetars are arguably the soft gamma-ray repeaters (SGRs), which have received ample attention after the giant flare of SGR 1806−20 on 2004 December 27, which had an energy of $\sim 10^{46}$ erg (e.g. Hurley et al. 2005). Related to the class of SGRs are the anomalous X-ray pulsars (AXPs), which are less prone to flare, although occasional flares have been observed (Gavriil, Kaspi & Woods 2002; Kaspi et al. 2003). Like SGRs they are radio-quiet X-ray pulsars with spin periods in the range of 5–12 s. The timing properties of both SGRs and AXPs suggest that they are isolated neutron stars, whereas their spin-down rate suggest that they have magnetar-like dipole magnetic fields of $B_{\rm dip} \sim 10^{14}$–10^{15} G (see Woods & Thompson 2004, for a review). Other arguments in favour of the magnetar hypothesis can be found in Thompson & Duncan (1995).

The apparent dichotomy between the radio-quiet magnetars, on the one hand, and ordinary young radio pulsars, with $B \sim 10^{12}$–10^{13} G, on the other, is likely to originate from distinct properties of the progenitor stars. One idea is that the high magnetic field of magnetars simply reflects the high magnetic field of their progenitor stars. Magnetic flux conservation (Woltjer 1964) implies that magnetars must then be the stellar remnants of stars with internal magnetic fields of $B \gtrsim 10^4$ G, whereas radio pulsars must be the end products of stars with $B \sim 10^3$ G. Based on a study of magnetic white dwarfs, Ferrario & Wickramasinghe (2006) argue that there is a wide spread in white dwarf progenitor magnetic fields, which, when extrapolated to the more massive progenitors of neutron stars, can explain the existence of magnetars.

A currently more popular idea for the origin of magnetars is that they are formed from proto-neutron stars with periods in the range $P_{\rm i} \sim 0.6$ ms (the break-up limit) to 3 ms. Convection and differential rotation in such rapidly rotating stars would give rise to an efficient α–Ω dynamo, resulting in magnetic field amplification on a time-scale of $\lesssim 10$ s (Duncan & Thompson 1992; Thompson & Duncan 1993; Duncan & Thompson 1996). In contrast, radio pulsars presumably start their life with initial spin periods of $\gtrsim 10$ ms

★E-mail: j.vink@astro.uu.nl

© 2006 The Authors. Journal compilation © 2006 RAS

or longer. As initially pointed out by Duncan & Thompson (1992), the idea that magnetars form from proton-neutron stars with $P \sim 1$ ms implies that supernova explosions that create magnetars are an order of magnitude more energetic than ordinary core-collapse supernovae. The reason is that a neutron star spinning with $P = 1$ ms ($\Omega = 6.3 \times 10^3$ s^{-1}) has a rotational energy of $E_{\rm rot} = 1/2\, I\Omega^2 \approx 3 \times 10^{52}$ $(P/1\,{\rm ms})^{-2}$ erg, for a moment of inertia of $I \approx 1.4 \times 10^{45}$ g cm^2 (Lattimer & Prakash 2001). Due to the high magnetic field, the magnetar rapidly spins down during the explosion, thereby powering the supernova. An upper limit for the time-scale in which most of the rotational energy is lost by a neutron star with $B = 10^{15}$ G is obtained by assuming magnetic braking in a vacuum, $\tau \approx 160$ s. More detailed modelling by Thompson, Chang & Quataert (2004) indicates that the time-scale for spin down of the proto-neutron star may be as short as 10–100 s.

Given the implication of the millisecond proto-neutron star hypothesis that magnetars should be surrounded by *hyper*nova remnants, it is surprising that this idea has not directly been tested on supernova remnants (SNRs) associated with AXPs and SGRs, although Allen & Horvath (2004) did calculate the effect of the hypernova/magnetar connection on the evolution of the SNR, and applied this to known magnetar/SNR connections. Here we review what is known about the explosion energies of the supernova remnants Kes 73, N49 and CTB 109 associated with, respectively, the magnetar candidates AXP 1E1841−045, SGR 0526−66, and AXP 1E2259+586. For CTB 109 and N49 explosion energy estimates have been given in the literature, but without discussing the possible implications for the magnetar formation scenario. As far as we know, no explosion energy estimates exist for Kes 73; we therefore present our own energy estimate based on archival *XMM–Newton* observations. In addition we present an analysis of the explosion energy of N49, also based on unpublished *XMM–Newton* data.

2 THE EXPLOSION ENERGIES OF SUPERNOVA REMNANTS ASSOCIATED WITH MAGNETARS

Gaensler (2004) reviewed the association of AXPs and SGRs with SNRs, taking into account the probability of random spatial coincidence given the extent of the SNR and the location of the AXP or SGR within the SNR. He concludes that magnetar candidates likely to be associated with SNRs (i.e. have a chance alignment probability <1 per cent) are: AXP 1E1841−045 with Kes 73 (G27.4+0.0), AXP 1E2259+586 with CTB 109 (G109.1−1.0), SGR 0526−66 with N49, and the candidate AXP AX J1845−045 with G29.6+0.1.

G29.6+0.1, a shell-type SNR, was detected in archival radio data (Gaensler, Gotthelf & Vasisht 1999) following the discovery of AX J1845−045 (Gotthelf & Vasisht 1998). Unfortunately, the X-ray emission from the SNR is too weak (Vasisht et al. 2000) and the distance too poorly constrained (Gaensler et al. 1999) to derive any meaningful energy estimate from the X-ray spectrum of the SNR. This leaves us with Kes 73, N49 and CTB 109 to test whether SNRs with magnetars are an order of magnitude more energetic than regular SNRs.

One can determine the energy of SNRs using the well-known Sedov evolution of an adiabatic point explosion in a uniform medium (Truelove & McKee 1999). The shock radius, $r_{\rm s}$, and velocity, $v_{\rm s}$, of such an explosion evolve as

$$r_{\rm s}^5 = \frac{2.026 E t^2}{\rho_0}, \quad (1)$$

$$v_{\rm s} = \frac{2 r_{\rm s}}{5t}, \quad (2)$$

with ρ_0 the interstellar medium density, E the explosion energy and t the age of the SNR. The shock velocity can be determined from X-ray spectra, because for a monatomic gas and high Mach number shocks the following relation holds between post-shock plasma temperature and shock velocity:

$$kT = \frac{3}{16} 0.63 m_{\rm p} v_{\rm s}^2, \quad (3)$$

with $m_{\rm p}$ the proton mass. The factor 0.63 gives the average particle mass in units of the proton mass. It is smaller than the proton mass, because it includes electrons. Thus, from measuring the temperature one can estimate $v_{\rm s}$, which, combined with the measured radius, gives the age of the SNR (equations 1 and 2). The interstellar medium density can be estimated from the X-ray emission measure (EM $= \int n_{\rm e} n_{\rm H}\, {\rm d}V$). Having obtained a density estimate, the explosion energy can be calculated using equation (1).

We list the results of our analysis of *XMM–Newton* data in Table 1, together with the parameters for CTB 109 reported by Sasaki et al. (2004). It is clear that these SNRs with magnetars do not have an order of magnitude higher explosion energies than the canonical supernova explosion energy of 10^{51} erg. More details about our analysis data can be found in the appendix, which also includes a short discussion on the effects of non-equilibration of temperatures on the derived parameters, and on the applicability of the Sedov model for Kes 73. Fig. 1 shows the *XMM–Newton* spectra of Kes 73 and N49 with best-fitting spectral models.

For all three SNRs the distances are well determined. N49 is located in the Large Magellanic Cloud, Kes 73 has a reliable distance estimate based on H I absorption measurements (d = 6–7.5 kpc, Sanbonmatsu & Helfand 1992), and CTB 109 cannot be more distant than Cas A, which is situated at 2° from CTB 109, has a higher absorption column, and is at a distance of 3.4 kpc (Reed et al. 1995). Both CTB 109 and Cas A are likely to be associated with the Perseus arm at ∼3 kpc.

As an aside, Cas A contains a point source that is suspected to be a magnetar (see Pavlov, Sanwal & Teter 2004, for a discussion), a suspicion that has gained more credibility with the recent discovery of an infrared light echo from a putative SGR-like giant flare (Krause

Table 1. The explosion energies and ages of the supernova remnants from X-ray spectral analysis.

SNR/Pulsar	Distance (kpc)	radius (pc)	E (10^{51} erg)	$n_{\rm H}$ (cm^{-3})	Mass ($M_\odot$)	SNR Age (10^3 yr)	Pulsar Age (10^3 yr)	References
Kes 73/1E1841−045	7.0	4.3	0.5 ± 0.3	2.9 ± 0.4	29 ± 4	1.3 ± 0.2	4.3	This work
CTB109/1E2259+586	3.0	10	0.7 ± 0.3	0.16 ± 0.02	97 ± 23	8.8 ± 0.9	220	Sasaki et al. (2004)
N49/SGR 0526−66	50	9.3	1.3 ± 0.3	2.8 ± 0.1	320 ± 50	6.3 ± 1.0	1.9	This work

Note that Sasaki et al. (2004) find an energy of $(1.9 \pm 0.7) \times 10^{51}$ erg for CTB109, if they assume incomplete temperature equilibration at the shock front. Derived energies scale with distance d as $d^{2.5}$. Distances and pulsar ages ($\tau = \frac{1}{2} P/\dot{P}$) are taken from Woods & Thompson (2004).

© 2006 The Authors. Journal compilation © 2006 RAS, MNRAS **370,** L14–L18

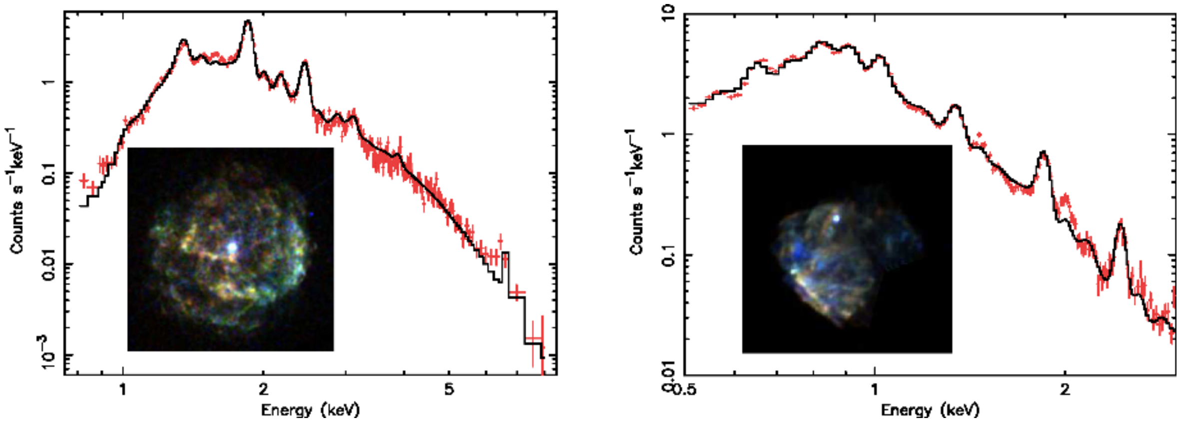

Figure 1. *XMM–Newton* MOS12 spectra of Kes 73 (left) and N 49 (right). The solid lines represent the best-fitting Sedov models. See appendix for details. *Chandra* ACIS images (taken from the archive) are shown as insets. The RGB colour-coding for Kes 73 corresponds to the energy ranges: 0.6–1.5 keV, 1.5–2.8 keV, 2.8–5 keV. The image measures 5.1 × 5.1 arcmin^2. The N49 images consists of a mosaic, and the RGB colours correspond to 0.5–0.75, 0.75–1.2 and 1.2–3 keV. The image measures 1.9 × 1.9 arcmin^2, but due to the small window mode of the observations the south-western corner of N49 is missing. AXP 1E1841-045 is the bright unresolved source in the center of Kes 73; SGR 0526−66 is the unresolved source near the northern edge of N49. For both images a linear brightness scaling was used, but saturating the unresolved sources in order to bring out the SNR emission.

et al. 2005). However, Cas A appears to have an explosion energy of $\sim 2 \times 10^{51}$ erg, which is quite accurately known, as the expansion has been directly measured (Vink 2004, for a review).

We like to conclude this section by pointing out that, although there are some uncertainties associated with determining the explosion energies using a Sedov analysis (gradients in the medium in which the SNR evolves, conversion of part of the energy to cosmic rays), these uncertainties apply equally to all other SNRs for which energies have been determined. Nevertheless, other SNRs appear to have similar explosion energies (Hughes, Hayashi & Koyama 1998). In other words, the most remarkable feature of SNRs with magnetars is that they are unremarkable, i.e. they are indistinguishable from normal SNRs.

3 DISCUSSION

This study shows that *in general* magnetar formation is not accompanied by a hypernova explosion. This does not necessarily preclude the idea that observed extragalactic hypernovae, such as SN1998bw, are not by the formation of a rapidly spinning magnetar followed by rapid magnetic braking (Nakamura 1998; Thompson et al. 2004), but it poses a challenge to the hypothesis that magnetars are formed as a result of magnetic field amplification in a rapidly spinning ($P \sim 1$ ms) proto-neutron star.

Note that when the magnetar theory of SGRs and AXPs was first proposed, the existence of magnetars was hardly an established fact (Duncan & Thompson 1992; Thompson & Duncan 1993). Today their existence is only doubted by a few, especially after the giant flare of SGR 1806−20. In general, SGR flare luminosities exceed the Eddington luminosity, making it hard to find any other source of energy but the internal magnetic field. The energy of the giant flare of SGR 1806−20 was $\sim 10^{46}$ erg (Hurley et al. 2005). If a neutron star has several of those flares this energy can only be provided with an internal magnetic field of $\sim 10^{16}$ G (e.g. Stella et al. 2005). Moreover, the results presented do not rule out initial periods of ~ 3 ms, the upper limit at which the α–Ω dynamo may operate (Duncan & Thompson 1996).

The generation of such a high internal magnetic field poses challenges in itself. The magnetar-sized magnetic fields may either derive from a high magnetic field in the core of the neutron star progenitor (the fossil field hypothesis), or may be generated in the proto-neutron star, in which case rapid rotation and strong convective motions and/or differential rotation are needed. It is indeed shown that proto-neutron stars are highly convective (Buras et al. 2006; Fryer & Warren 2004), although Fryer & Warren (2004) express some doubt whether it is sufficient to generate magnetic fields in excess of 10^{14} G. The rapid rotation needed for amplifying magnetic fields in proto-neutron stars may reflect the high angular momentum of the core of the progenitor. However, the proto-neutron star may also wind up due to asymmetric accretion during collapse, in which case it is expected that the accretion results in both additional spin and kick velocity (Spruit & Phinney 1998; Thompson 2000).

For the fossil field hypothesis, the solution to the question of the origin of the magnetic field creates a new problem, namely, the origin of the high magnetic field of the progenitor star. It could be that the magnetic field is again the result of the amplification of a seed magnetic field due to rotation and convection, but in this case in the core of the progenitor. However, as noted by Thompson & Duncan (1993), there is less convective energy available during any stage of stellar evolution, than during the proto-neutron star phase. Another option is what one might call the strong fossil field hypothesis: the magnetic field in the star reflects the magnetic field of the cloud from which the star was formed.

Ironically, stellar evolution models indicate that progenitors with a high magnetic field in the core end up producing more slowly rotating pulsars (Heger, Woosley & Spruit 2005). This is a result of the more effective coupling of angular momentum of the core to the outer radius of the star, where angular momentum is lost due to stellar winds.

The results presented here are in agreement with the fossil field hypothesis. Recently, Ferrario & Wickramasinghe (2006) showed that the magnetic flux distribution of magnetic white dwarfs and neutron stars are similar. Translated to neutron star radii, the highest magnetic field measured in white dwarfs corresponds to 10^{14}–10^{15} G. However, this falls still short of the 10^{16} G needed to power flares from SGRs such as SGR 1806−20. Possibly this could be accounted for by additional magnetic field amplification during the late stages of stellar evolution of stars that end in a core collapse (cf. the core magnetic field evolution of the magnetic star of Heger et al. 2005).

On the other hand, the energetics of the SNRs with magnetars could still be reconciled with magnetic field amplification in a rapidly rotating proto-neutron star, provided the angular momentum is not lost by magnetic braking, in which case it powers the supernova, but due to gravitational radiation or due to emission in a jet (see also Thompson & Duncan 1993). Such a loss mechanism should work on a time-scale shorter than the magnetic braking time-scale, i.e. less than a few hundred seconds.

Stella et al. (2005) argued recently that if *internal* magnetic fields exceed 5×10^{16} G, the deformation of the neutron stars is sufficiently strong to cause gravitational waves that radiate away most of the rotational energy. Note, however, that this is only true if rotation losses due to gravitational waves exceed losses due to magnetic braking. This requires $B_{\rm i} > 5 \times 10^{16}$ G, for which no conclusive evidence exists yet, whereas the external dipole field has to be low, $B_{\rm d} < 5 \times 10^{14}$ G. Moreover, this estimate is based on magnetic braking in a vacuum, whereas during the first few seconds magnetic braking is likely to be enhanced due to the presence of the hot plasma surrounding the proto-neutron star (Thompson et al. 2004).

It is possible that in the early phase of a magnetar the dipole field is indeed low. On the other hand, the observed dipole fields are lower than is required to slow down to the spin periods of AXPs and SGRs. A case in point is 1E1841-045/Kes73, for which we determined an age of $\sim$1300 yr. To bring it from a period of few ms to its current period (11.8 s), a dipole field of 1.6×10^{15} G is required for a braking index of $n = 2.5$. Gravitational waves cannot explain this, as only for very short periods do gravitational wave losses dominates over magnetic braking, because rotation loss scales with Ω^5 for gravitational waves and with Ω^3 for magnetic braking.

Another consequence is that as soon as magnetic braking dominates one expects the creation of a strong a pulsar wind nebula. Intriguingly, none of the magnetars studied here show any evidence for a pulsar wind component. The radio map of Kes 73 shows, in fact, that the AXP is located in a hole in the SNR (Kriss et al. 1985). In X-rays we do not expect to see a pulsar wind nebula, as the ultrarelativistic electrons responsible for X-ray synchrotron emission will have lost most of their energy. Note that the spin-down of a magnetar like 1E1841−045 is so rapid that the pulsar wind nebula must evolve during the early, free expansion phase of the SNR. Because most of the ejecta has not been shocked, it is possible that the relativistic particles freely escape instead of being confined by the hot plasma of the SNR. However, it would be of great importance to investigate the formation of pulsar wind nebulae from magnetars in more detail, as it may provide additional means of determining whether AXP and SGRs started with periods in the millisecond range.

Finally, another way of losing angular momentum is by means of a jet during the explosion. Radio and X-ray maps of Kes 73 and N49 do not show evidence that a jet may have been present in the past. Kes 73 is in fact remarkably circularly symmetric (Fig. 1). Interestingly, however, there is considerable evidence for a jet in the SNR Cas A (Fesen 2001; Vink 2004; Hwang et al. 2004), and there is indeed evidence, although not conclusive, that the point source in Cas A is a magnetar (Krause et al. 2005).

ACKNOWLEDGMENTS

JV thanks Andrew MacFadyen, Nanda Rea, Robert Duncan and the referee, Chris Thompson, for helpful discussions and suggestions.

REFERENCES

Allen M. P., Horvath J. E., 2004, ApJ, 616, 346
Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, ASP Conf. Ser., Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Borkowski K. J., Lyerly W. J., Reynolds S. P., 2001, ApJ, 548, 820
Buras R., Rampp M., Janka H.-T., Kifonidis K., 2006, A&A, 447, 1049
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Duncan R. C., Thompson C., 1996, in Rothschild R., Lingenfelter R., eds, AIP Conf. Proc., 366, High Velocity Neutron Stars and Gamma-Ray Bursts. Am. Inst. Phys., New York, p. 111
Ferrario L., Wickramasinghe D., 2006, MNRAS, 367, 1323
Fesen R. A., 2001, ApJS, 133, 161
Fryer C. L., Warren M. S., 2004, ApJ, 601, 391
Gaensler B. M., 2004, Adv. Space Res., 33, 645
Gaensler B. M., Gotthelf E. V., Vasisht G., 1999, ApJ, 526, L37
Gavriil F. P., Kaspi V. M., Woods P. M., 2002, Nat, 419, 142
Gotthelf E. V., Vasisht G., 1998, New Astron., 3, 293
Heger A., Woosley S. E., Spruit H. C., 2005, ApJ, 626, 350
Hughes J. P., Hayashi I., Koyama K., 1998, ApJ, 505, 732
Hurley K. et al., 2005, Nat, 434, 1098
Hwang U. et al., 2004, ApJ, 615, L117
Kaastra J. S., Mewe R., 2000, in Bautista M. A., Kallman T. R., Pradhan A. K., eds, Atomic Data Needs for X-ray Astronomy. NASA, Washington, p. 161
Kaspi V. M. et al., 2003, ApJ, 588, L93
Krause O. et al., 2005, Sci, 308, 1604
Kriss G. A. et al., 1985, ApJ, 288, 703
Lattimer J. M., Prakash M., 2001, ApJ, 550, 426
Nakamura T., 1998, Prog. Theor. Phys., 100, 921
Park S. et al., 2003, ApJ, 586, 210
Pavlov G. G., Sanwal D., Teter M. A., 2004, in Camilo F., Gaensler B. M., eds, Proc. IAU Symp., 218, Young Neutron Stars and Their Environments. Astron. Soc. Pac., San Francisco, p. 239
Rakowski C. E., 2005, Adv. Space Res., 35, 1017
Reed J. E., Hester J. J., Fabian A. C., Winkler P. F., 1995, ApJ, 440, 706
Sanbonmatsu K. Y., Helfand D. J., 1992, AJ, 104, 2189
Sasaki M. et al., 2004, ApJ, 617, 322
Spruit H. C., Phinney E. S., 1998, Nat, 393, 139
Stella L., Dall'Osso S., Israel G. L., Vecchio A., 2005, ApJ, 634, L165
Thompson C., 2000, ApJ, 534, 915
Thompson C., Duncan R. C., 1993, ApJ, 408, 194
Thompson C., Duncan R. C., 1995, MNRAS, 275, 255
Thompson T. A., Chang P., Quataert E., 2004, ApJ, 611, 380
Truelove J. K., McKee C. F., 1999, ApJS, 120, 299
Turner M. J. L. et al., 2001, A&A, 365, L27
Vasisht G., Gotthelf E. V., Torii K., Gaensler B. M., 2000, ApJ, 542, L49
Vink J., 2004, New Astron. Rev., 48, 61
Vink J. et al., 2003, ApJ, 587, 31
Woltjer L., 1964, ApJ, 140, 1309
Woods P., Thompson C., 2004, in Lewin W. H. G., van der Klis M., eds, Cambridge Astrophys. Ser. No. 39, Compact Stellar X-ray Sources. Cambridge Univ. Press, Cambridge, p. 547

APPENDIX A: THE SPECTRAL ANALYSIS OF *XMM–NEWTON* DATA OF KES 73 AND N49

For determining the energies of Kes 73 and N49 we used archival *XMM–Newton* data observations made on 2002 October 5 and 7 (Kes 73, ObsIDs 0013340101 and 0013340201) and of N49 made on 2000 July 7 and 2001 April 8 (N49, ObsIDs 0111130301 and 0113000201). We only used data from the MOS1 and MOS2 instruments, because they offer the best energy resolution (Turner et al. 2001). We processed the data in a standard manner employing the

XMM–Newton software SAS 6.5.0, excluding time intervals with excessive background flares. The source spectra were extracted from circular regions encompassing the source, excluding small circular regions containing the AXP or SGR. Background spectra were extracted from annular regions around the SNRs. For our final spectral analysis we added all the MOS1 and MOS2 spectra of each individual SNR together for statistical reasons, using exposure weighted merged response files (RMFs) and ancillary response files (ARFs), a procedure that makes for a nicer representation of the spectra and gives little loss of accuracy, as the two MOS detectors are similar. The total effective exposure per detector is 9.8 ks for Kes 73 and 39.6 ks for N49.

For the spectral analysis two spectral analysis packages were employed, SPEX (Kaastra & Mewe 2000) and XSPEC (Arnaud 1996). SPEX has the advantage that it includes more lines associated with inner shell ionization, which is important for non-equilibration ionization (NEI) plasmas. This is in particular relevant for Kes 73, which is more out of ionization equilibrium than N49[1] (Table A1). XSPEC contains a Sedov model (VSEDOV, Borkowski et al. 2001) that also includes non-equilibration of electron and ion temperatures, an effect that is known to be important for in particular SNRs with a short ionization age ($n_e t$) and high shock velocity (Rakowski 2005). We used SPEX for a more heuristic approach in which we fit the spectra with two non-equilibration ionization models with two different temperatures and ionization ages, but with elemental abundances of the two components coupled.

From the results listed in Table A1 one can calculate the pre-shock density using the relation for SNRs in the Sedov phase $\int n_e n_H \, dV = 0.129(4\pi/3)r_s^3$. The shock velocity can be obtained from equation (3), and using the relation between v_s, r_s and t (equation 1) one can then infer the age of the SNR. From the age and the pre-shock density an estimate of the explosion energy can be derived (equation 1). However, equation (3) does not apply in case the plasma is not in full temperature equilibration. Although both remnants have lower shock velocities and much larger ionization ages than a SNR like SN1006 for which this effect has in fact been measured ($n_e t = 2 \times 10^9$ cm^{-3} s, Vink et al. 2003), there may still be some effect, in particular for Kes 73. The plasma parameters of Kes 73 are in fact quite similar to those of CTB 109, for which Sasaki et al. (2004) argued that $T_p/T_e \leqslant 2.5$. We find that assuming non-equilibration for Kes 73 gives a more consistent result. The reason is that the age of the remnant can be estimated both from kT and from the ionization age. From $n_e t$ we derive $t = 1300 \pm 200$ yr, but using kT we find from the values in the second column of Table 1; 2145 ± 37 yr for full equilibration, but 1357 ± 23 yr if $T_p/T_e = 2.5$. For N49 the ionization age and temperature give consistent results assuming full equilibration (6.6 ± 0.9 and 6.1 ± 1.7 kyr, respectively). This is to be expected, as the ionization age of N49 corresponds roughly to the Coulomb equilibration time.

A note of caution concerning the interpretation of the X-ray spectrum of Kes 73: as Table A1 shows, there is considerable uncertainty about the abundance pattern of Kes 73, with the 2NEI model suggesting abundances that are almost solar, whereas the Sedov model suggest an enriched plasma. Other differences between the models in fact go back to this, because fitting the Sedov model with the abundances fixed at solar values we obtained a total emission measure and temperature closer to that of the 2NEI model. The matter is of some interest, as overabundances would be an indication that Kes 73 is in an early evolutionary state that cannot be well described by a Sedov model. Another possible indication for that is the low total mass of Kes 73 (25–33 M$_\odot$, for the 2NEI and Sedov models, respectively), much lower than N49 (320 M$_\odot$) or CTB 109 (97 ± 23 M$_\odot$, Sasaki et al. 2004). We consider the 2 NEI model to be more reliable in this case, as SPEX incorporates more line data relevant for NEI plasmas. In fact, Fig. 1 shows that the Fe–K complex around 6.6 keV and the Mg XII lines around 1.4 keV are not well fitted. The SPEX 2NEI model does not have these problems. Although the fits to the spectra of Kes 73 and N49 are not perfect, the global features of the spectra are well fitted (Fig. 1).

Nevertheless, we tried to constrain the explosion energy of Kes 73 further by exploring the more generic SNR evolution models of Truelove & McKee (1999). We tried to answer the question of which explosion energies are still consistent with the densities and post-shock temperatures found from our fit, 2–4 cm^{-3} and 0.6–1.9 keV, given the shock radius of 4 pc and assuming that the ejecta masses lie in the range 0.5–25 M$_\odot$. Considering ejecta density profiles with power indices of $n = 0$, $n = 7$, and $n = 9$ (see Truelove & McKee 1999), it turns out that the observational data is only consistent with energies in the range $(0.1 - 1.1) \times 10^{51}$ erg.

Table A1. Best-fitting spectral models to *XMM–Newton*/MOS1 data.

Model	Kes 73		N49
	2 NEI	Sedov	Sedov
EM (10^{12} cm^{-5})	26.9 ± 3.1	16.4 ± 1.5	5.4 ± 0.5
kT_e (keV)	0.63 ± 0.06	0.72 ± 0.3	0.415 ± 0.005
$n_e\, t$ (10^{11} cm^{-3} s)	3.1 ± 0.8	4.6 ± 0.2	28.0 ± 2.6
EM$_2$ (10^{12} cm^{-5})	2.0 ± 0.5		
kT_{2e} (keV)	2.26 ± 0.35		
$n_e\, t_2$ (10^{11} cm^{-3}s)	0.47 ± 0.10		
O	(1)	(1)	0.25 ± 0.02
Ne	(1)	(1)	0.41 ± 0.02
Mg	1.13 ± 0.13	1.95 ± 0.15	0.27 ± 0.01
Si	1.09 ± 0.07	1.7 ± 0.1	0.45 ± 0.01
S	1.12 ± 0.06	1.6 ± 0.1	0.99 ± 0.06
Ar	1.02 ± 0.18	1.1 ± 0.1	–
Ca	1.84 ± 0.42	0.77 ± 0.33	–
Fe	0.42 ± 0.15	4.3 ± 0.7	0.19 ± 0.01
N_H (10^{21} cm^{-2})	27.3 ± 0.6	31.2 ± 0.6	2.2 ± 0.1
Fit range (keV)	0.8–8.0	0.8–8.0	0.5–3.0
C-statistic/d.o.f.	186/110	956/468	574/153

Notes. Errors correspond to 68 per cent confidence ranges ($\Delta C = 1.0$). 'EM' refers to the emission measure [$\int n_e n_H \, dV/(4\pi d^2)$]. Abundances are given with respect to the solar abundances of Anders & Grevesse (1989). For Kes 73, the abundance of oxygen and neon were fixed to solar values, because the strong absorption did not allow for an accurate determination.

[1] For a recent detailed X-ray study of this SNR see Park et al. (2003).

This paper has been typeset from a TEX/LATEX file prepared by the author.