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A downward revision to the distance of the 1806−20 cluster and associated magnetar from Gemini Near-Infrared Spectroscopy

J. L. Bibby,[1]★ P. A. Crowther,[1] J. P. Furness[1] and J. S. Clark[2]

[1]*Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Rd, Sheffield S3 7RH*

[2]*Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA*

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ABSTRACT

We present *H*- and *K*-band spectroscopy of OB and Wolf–Rayet (WR) members of the Milky Way cluster 1806−20 (G10.0–0.3) to obtain a revised cluster distance, of relevance to the 2004 giant flare from the (soft gamma repeater) SGR 1806−20 magnetar. From GNIRS (Gemini Near-Infrared Spectrograph) spectroscopy obtained with Gemini South, four candidate OB stars are confirmed as late O/early B supergiants, while we support previous mid-WN and late WC classifications for two WR stars. Based upon an absolute K_s-band magnitude calibration for B supergiants and WR stars, and near-infrared (IR) photometry from NIRI (Near-Infrared Imager) at Gemini North plus archival VLT/ISAAC (Very Large Telescope/Infrared Spectrometer And Array Camera) data sets, we obtain a cluster distance modulus of 14.7 ± 0.35 mag. The known stellar content of the 1806−20 cluster suggests an age of 3–5 Myr, from which theoretical isochrone fits infer a distance modulus of 14.7 ± 0.7 mag. Together, our results favour a distance modulus of 14.7 ± 0.4 mag ($8.7^{+1.8}_{-1.5}$ kpc) to the 1806−20 cluster, which is significantly lower than the nominal 15 kpc distance to the magnetar. For our preferred distance, the peak luminosity of the 2004 December giant flare is reduced by a factor of 3 to 7×10^{46} erg s^{-1}, such that the contamination of BATSE (Burst And Transient Source Experiment) short gamma-ray bursts (GRBs) from giant flares of extragalactic magnetars is reduced to a few per cent. We infer a magnetar progenitor mass of $\sim 48^{+20}_{-8}$ M$_\odot$, in close agreement with that obtained recently for the magnetar in Westerlund 1.

Key words: stars: early-type – pulsars: individual: SGR 1806−20 – stars: Wolf–Rayet – Galaxy: kinematics and dynamics – open clusters and associations: individual: 1806−20.

1 INTRODUCTION

Magnetars are highly magnetized neutron stars, representing a small subset of slowly rotating pulsars undergoing rapid spin down, and are observationally associated with anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs). To date only four examples of SGRs are known, characterized by multiple, soft gamma-ray bursts (GRBs), typically 10^{41} erg s^{-1} in peak luminosity, plus rare giant flares of 10^{45} erg s^{-1} peak luminosity. One such giant flare, from SGR 1806−20 (Kouveliotou et al. 1998), was detected on 2004 December 27 by many satellites including the Burst Alert Telescope (BAT) on *Swift* (Palmer et al. 2005), and in 2005 January the radio afterglow was detected by Cameron et al. (2005) through Very Large Array (VLA) observations.

It is believed that massive stars are the progenitors of magnetars, on the basis that several magnetars are associated with young massive clusters, including SGR 1806−20 which is apparently within a cluster at G10.0–0.3, forming part of the W31 complex. However, a distance of 12–15 kpc has been proposed for the 1806−20 cluster (Eikenberry et al. 2004; Figer, Najarro & Kudritzki 2004), yet direct H I measurements for the magnetar suggest 6–10 kpc (Cameron et al. 2005), though the latter has been questioned by McClure-Griffiths & Gaensler (2005).

Adopting a distance of 15 kpc suggests SGR 1806−20 had a peak luminosity of 2×10^{47} erg s^{-1} during the 2004 December giant flare, meaning magnetars at distances of up to 30 Mpc could be mistaken for short GRBs. For this distance, as much as 40 per cent of all short GRBs identified by the Burst And Transient Source Experiment (BATSE) might be giant flares (Hurley et al. 2005), falling to just 3 per cent if a distance of ∼6 kpc were adopted for SGR 1806−20.

The cluster contains young massive stars including OB stars, Wolf–Rayet (WR) stars and a luminous blue variable (LBV; van Kerkwijk et al. 1995; Eikenberry et al. 2004; Figer et al. 2004). If the magnetar is physically associated with this cluster and lies at 15 kpc then a high mass for the LBV, and hence the magnetar progenitor, of >133 M$_\odot$ is indicated (Eikenberry et al. 2004). However, this is much larger than the 40–55 M$_\odot$ progenitor of the

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★E-mail: j.bibby@sheffield.ac.uk

AXP found in Westerlund 1, whose stellar content is reminiscent of the SGR 1806−20 cluster (Muno et al. 2006; Clark et al. 2008).

In this Letter, spectra of several massive stars within the cluster are presented in Section 2. In Section 3, spectral types are determined together with estimates of absolute magnitude for each star. This allows the cluster distance and age to be obtained in Section 4 and compared to that of the magnetar. Conclusions are drawn in Section 5.

2 OBSERVATIONS

Spectroscopic data of 1806−20 cluster members were obtained from the Gemini Near-Infrared Spectrograph (GNIRS) instrument at Gemini South. New near-infrared (IR) photometry was provided by the Near-Infrared Imager (NIRI) instrument at Gemini North,[1] supplemented by Very Large Telescope (VLT) Infrared Spectrometer And Array Camera (ISAAC) and New Technology Telescope (NTT) Son of ISAAC (SofI) archival observations.

2.1 Photometry

NIRI *H*-band acquisition images of the 1806−20 cluster were obtained on 2007 July 13–14 during conditions with an image quality of ∼0.35 arcsec (3 pixel) full width at half-maximum (FWHM). Two Micron All Sky Survey (2MASS) *H*-band photometry of isolated, bright sources 2, 6, 11 and 12 from Figer et al. (2004) provided a zero-point, from which errors of ± 0.03 mag were obtained. In addition K_s-band archival VLT ISAAC images from 2005 March 17 (program 274.D.5048) obtained with an image quality of 0.4 arcsec (2.4 pixel FWHM), plus 2MASS K_s-band photometry of the same bright sources as used with NIRI provided zero-points and errors of ±0.02 mag. In the case of star B from Eikenberry et al. (2004) the ISAAC images were saturated. For this star we resorted to archival NTT SofI K_s-band images from 2003 July 31 (program 271.D.5041) for which an image quality of FWHM ∼1.1 arcsec (8 pixel) was measured, again with zero-points from 2MASS and errors of ±0.1 mag.

2.2 Spectroscopy

We used the GNIRS instrument on the 8-m Gemini South telescope at Cerro Pachon, Chile on 2007 April 8–9 to observe a number of massive stars associated with cluster 1806−20 during *K*-band seeing conditions of FWHM ∼0.5 arcsec. Spectroscopic data were obtained in the *H* band over a wavelength range 1.625–1.775 μm and in the *K* band for 2.025–2.225 μm. The slit width was 3 pixels (0.45 arcsec), providing a resolution $R \sim 3700$. Individual exposures of 270 s (*H* band) and 80 s (*K* band) were combined producing total exposures of 640–960 s (*K* band) and 2160–3240 s (*H* band).

The telescope was nodded along three slit positions of differing position angle, allowing observations of star C from Eikenberry et al. (2004) plus stars 1, 2, 4, 7 and 11 from Figer et al. (2005), which allowed pairs of images for sky subtraction. Internal argon lamp images were obtained immediately before or after each slit position, providing an accurate wavelength calibration. Further spectra were obtained for the telluric standard star HIP 89384 (B6 V) with an identical set-up, except reduced exposure times of 30 s in both the *H* and *K* band, for which sky lines were used to provide a wavelength calibration. Calibration flat fields and dark frames were also obtained.

Initial data reduction (sky subtraction, flat-fielding and wavelength calibration) was done using the Image Reduction and Analysis Facility (IRAF)[2] then spectra for each object observed were extracted. STARLINK packages were then used to telluric correct and normalize the spectra. Stellar Brackett lines from the telluric standard star were fit using empirical profiles from high spectral resolution observations of late B/early A dwarfs of Hanson et al. (2005).

3 SPECTROSCOPY OF 1806−20 CLUSTER MEMBERS

We supplemented GNIRS observations of stars 1, 2, 4, 7 and 11 from Figer et al. (2005) with their observations of star 3 plus GNIRS spectroscopy of star C from Eikenberry et al. (2004) with their observations of stars B and D. After reduction and calibration, the observed spectra were compared to template stars from the spectral atlases of Hanson et al. (2005) for OB stars and Crowther & Smith (1996) for WR stars.

3.1 OB stars

In Fig. 1, GNIRS spectra of cluster OB stars are compared to template supergiants from Hanson et al. (2005). In the *H* band, stars C and 7 clearly shows He I 1.700 μm absorption but the He II 1.692 μm line is not present, indicating that they are early B stars. Star C shows strong Br 10 absorption supporting a classification of B1–B3 I. Similarly, star 7 shows a relatively weak Br 10 line, indicating B0–B1 I. *K*-band observations support these classifications since the presence of the N III 2.115 μm emission in star 7 is common to B0–B1 supergiants, where N III 2.115 μm absorption in star C is shared with B1–B3 supergiants. Later subtypes are excluded from the observed strength of He I features, and again no evidence for He II 2.189 μm is seen.

Star 11 shows relatively weak Br 11 1.681 μm and Br 10 1.736 μm absorption in the *H* band, indicating a B0 I spectral type, whilst its *K*-band spectra is ambiguous due to the lack of Br γ, as noted by Figer et al. (2005). Weak He II 2.189 μm absorption is present in star 4, supporting an O9.5 I spectral classification.

In all these cases OB supergiant classifications proposed by Eikenberry et al. (2004) and Figer et al. (2005) are supported for which we are able to provide more refined subtypes, albeit unable to distinguish between Ia and Ib luminosity classes.

3.2 WR stars

Star 1 from Figer et al. (2005) has previously been identified as a WC 8 star. However, inspection of GNIRS spectroscopy in Fig. 2 reveals that the relative strength of the C IV 1.736 μm to the He I 1.700 μm emission is too low for a WC 8 star and is more typical of dusty WC 9 stars such as WR 121. Moreover, the C IV 2.076 μm/C III 2.110 μm ratio is consistent with other observations of dusty WC 9 stars by Crowther et al. (2006a). Warm circumstellar dust contributes to their near-IR flux, resulting in emission lines appearing relatively

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[1] Following severe damage to GNIRS in 2007 April, spectroscopy of additional 1806−20 cluster members were obtained with NIRI at Gemini North, but these did not improve on previously published work due to a misaligned slit and low spectral resolution.

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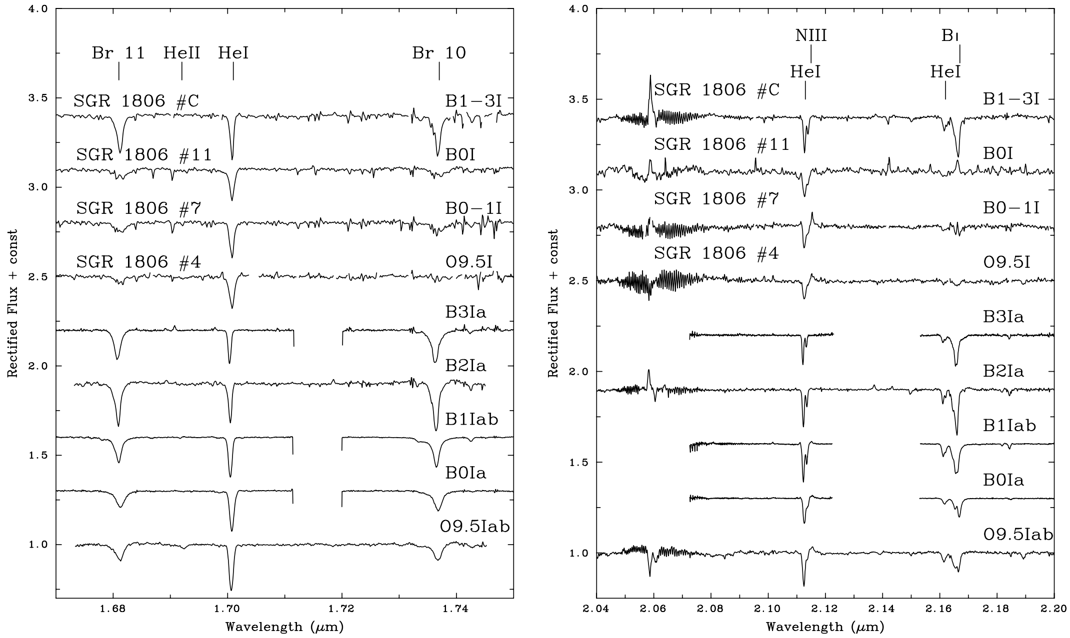

Figure 1. Spectral comparison between OB stars in the 1806−20 cluster and template spectra from Hanson et al. (2005) in the *H* band (left) and *K* band (right). The structure around λ = 2.06 μm is due to the imperfect telluric correction.

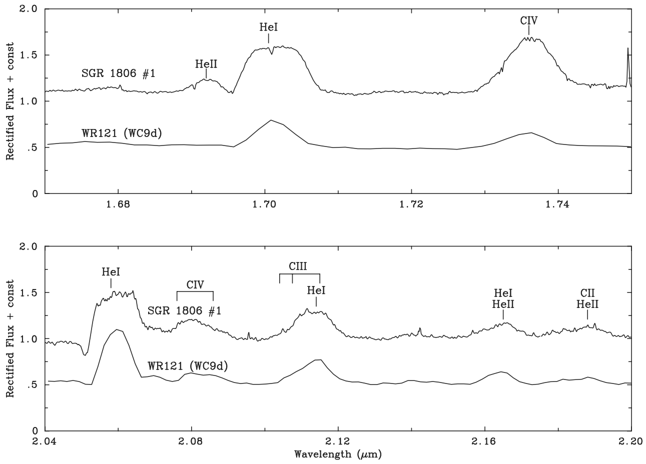

Figure 2. Spectral comparison of #1 from Figer et al. (2005) in the 1806−20 cluster with the galactic dusty WC 9 star WR 121 in the *H* (upper panel) and *K* (lower panel) band.

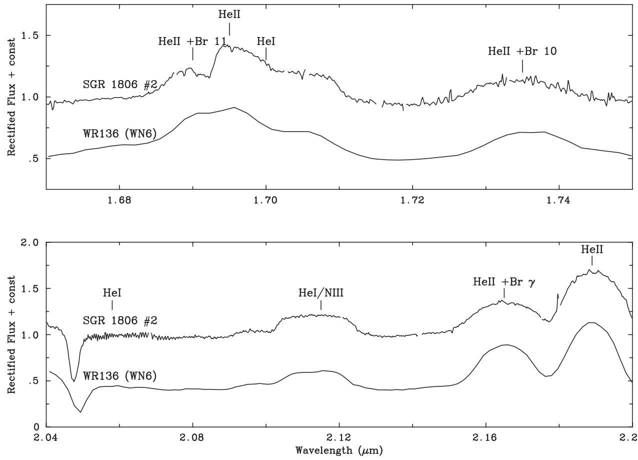

Figure 3. Spectral comparison of #2 from Figer et al. (2005) in the 1806−20 cluster with WR 136 (WN 6b) in the *H* (upper panel) and *K* (lower panel) band.

weak with respect to non-dusty WC 9 stars, for example WR 88 from Eenens, Williams & Wade (1991), from which a WC 9d spectral type results for star 1.

The GNIRS spectra for star 2 presented in Fig. 3 produces a classification of a broad-lined WN 6 star (WN 6b), in agreement with Figer et al. (2005). This is evident from the strong He II 2.189 μm emission compared to the weaker He I/N III 2.115 μm and Br γ emission. A later WN classification would require a higher Br γ to He II 2.189 μm ratio (Crowther et al. 2006a).

4 DISTANCE TO 1806−20 CLUSTER

We are now in a position to determine the distance to the 1806−20 cluster from both spectroscopic methods, using absolute magnitude versus spectral type calibrations for OB and WR stars and from fitting isochrones to the position of OB supergiants in the Hertzsprung–Russell (HR) diagram.

4.1 Absolute magnitude calibration

The near-IR absolute magnitude calibration for O stars (Martins & Plez 2006) does not extend to early B supergiants. Consequently, absolute *visual* magnitude calibration of B supergiants from Conti, Crowther & Leitherer (2008) are used together with synthetic near-IR intrinsic colours of early B supergiants from Crowther, Lennon & Walborn (2006b) to obtain a K_s-band absolute magnitude calibration, as shown in Table 1. The empirical spread in our OB supergiant calibration is estimated to be ±0.5 mag. For comparison, at O9.5 I,

Table 1. Adopted absolute K_s-band magnitude calibration for early B supergiants based on absolute visual magnitudes from Conti et al. (2008), intrinsic near-IR colours and bolometric corrections ($\mathrm{BC}_{K_\mathrm{s}}$) from Crowther et al. (2006a).

Sp type	M_V	$(V-K_\mathrm{s})_0$	$(H-K_\mathrm{s})_0$	M_{K_s}	$\mathrm{BC}_{K_\mathrm{s}}$
O9.5 I	-6.4 ± 0.5	-0.71	-0.08	-5.7 ± 0.5	-3.4
B0 I	-6.6 ± 0.5	-0.75	-0.08	-5.85 ± 0.5	-3.3
B1 I	-6.9 ± 0.5	-0.62	-0.08	-6.3 ± 0.5	-2.65
B2 I	-7.1 ± 0.5	-0.53	-0.08	-6.6 ± 0.5	-2.1
B3 I	-7.1 ± 0.5	-0.36	-0.05	-6.7 ± 0.5	-1.7

which is common to both calibrations, Martins & Plez (2006) obtain $M_K = -5.52$ mag, $(H - K) = -0.10$ mag and $\mathrm{BC}_K = -3.66$ mag.

For WR stars, absolute magnitudes from Crowther et al. (2006a) were used for calibration, with a typical spread of ±0.7 mag. Intrinsic colours are drawn from the same sources with typical uncertainties of ±0.05 mag. Dusty WC stars span a much wider range in both absolute magnitude ($M_K = -8.5 \pm 1.5$ mag) and intrinsic colour [$(H - K)_0 = 1.1 \pm 0.6$] at near-IR wavelengths than normal WC stars, preventing their use as reliable distance indicators (Crowther et al. 2006a).

4.2 Spectroscopic distance

Observed colours of OB and WR stars in the 1806−20 cluster provide a direct measurement of interstellar extinction from $A_{K_\mathrm{s}} = 1.82^{+0.30}_{-0.23} E_{H-K_\mathrm{s}}$ (Indebetouw et al. 2005). These are presented in Table 2, from which a mean $A_{K_\mathrm{s}} \sim 3.0 \pm 0.3$ mag is obtained, together with distance moduli for each star, based upon absolute magnitude calibrations, from which dusty WC stars were excluded, as explained above. A mean distance modulus of 14.69 ± 0.35 mag results from this spectroscopic study, corresponding to $8.7^{+1.5}_{-1.3}$ kpc.

4.3 Distance from isochrone fitting

Alternatively, theoretical isochrones may be used to estimate the distance to the 1806−20 cluster if limits upon the cluster age are available. As noted above, this cluster hosts OB stars, an LBV, together with helium burning WN and WC stars, a stellar content in common with other massive star clusters within the inner Milky Way. These include Westerlund 1 and the Quintuplet cluster, for which ages of 4–5 Myr and 4 ± 1 Myr have been inferred by Crowther et al. (2006a) and Figer, McLean & Morris (1999), respectively.

OB supergiants #4 (O9.5 I) and 11 (B0 I) have the best determined spectral types, from which stellar temperatures (29 and 27.5 kK) and luminosities can be derived (Crowther et al. 2006b), the latter obtained from K_s-band bolometric corrections ($\mathrm{BC}_{K_\mathrm{s}}$, see Table 1). For a variety of different adopted distances, these two stars provide cluster ages using isochrones from Lejeune & Schaerer (2001), which are based upon high mass-loss rate, solar metallicity evolutionary models from Meynet et al. (1994). Table 3 presents ages, OB supergiant and (minimum) magnetar initial masses for distance moduli in the range 14.0 mag (6.3 kpc) to 15.9 mag (15 kpc). Large distances would require these stars to be hypergiants, characterized by an emission line spectrum, for which there is no spectroscopic evidence. From above a distance modulus of 14.7 ± 0.7 mag (6.3–12 kpc) is obtained, together with a magnetar progenitor mass of 35–100 $\mathrm{M}_\odot$.

4.4 Comparison with previous work

Together these two methods of estimating the distance to the 1806−20 cluster suggest a distance modulus of 14.7 ± 0.4 mag ($8.7^{+1.8}_{-1.5}$ kpc). This is substantially lower than the nominal ∼15 kpc kinematic distance to the magnetar obtained by Corbel et al. (1997) from CO observations which was supported by Eikenberry et al. (2004) from the nebular Br γ emission (local standard of rest) velocity for LBV 1806−20. In Fig. 4 the cluster distance from this work is compared to Eikenberry et al. (2004) and Figer et al. (2004), adapted to a Galactic Centre distance of 8 kpc (Reid 1993) and the Brand & Blitz (1993) rotation model. In addition, magnetar distances from Corbel et al. (1997), Cameron et al. (2005) and McClure-Griffiths & Gaensler (2005) are included, also updated for a Galactic Centre distance of 8 kpc.

Our distance reconciles the previously inconsistent cluster and magnetar distances. In addition, OB supergiant stellar He I 1.700 μm and Br γ line profiles from GNIRS reveal $V_\mathrm{LSR} \sim 130\,\mathrm{km\,s^{-1}}$, indicating kinematic distances of either 6.8 or 8.9 kpc, in good agreement with both the spectroscopic parallax and isochrone fitting methods (previous studies implied $V_\mathrm{LSR} = 10$–$35\,\mathrm{km\,s^{-1}}$, from Corbel et al. 1997; Figer et al. 2004.)

5 DISCUSSION AND CONCLUSIONS

A revised distance of $\sim 8.7^{+1.8}_{-1.5}$ kpc to the 1806−20 cluster is obtained from this work, reconciling previous cluster and magnetar distances, from which a magnetar progenitor mass of $\sim 48^{+20}_{-8}\,\mathrm{M}_\odot$ is inferred, consistent with estimates for the Westerlund 1 magnetar (AXP) from Muno et al. (2006) and Clark et al. (2008). Similar

Table 2. Spectral classifications and photometry of 1806−20 cluster members together with interstellar extinctions A_{K_s}, adopted absolute magnitudes M_{K_s} and resulting distance moduli (DM).

Star	Sp type	K_s (mag)	$H-K_\mathrm{s}$ (mag)	$(H-K_\mathrm{s})_0$ (mag)	E_{H-K_s} (mag)	A_{K_s} (mag)	M_{K_s} (mag)	DM (mag)
#1	WC 9d	11.60	2.16	+1.10	1.06			
#2	WN 6b	12.16	1.89	+0.27	1.62	2.95 ± 0.5	-4.77 ± 0.7	13.98 ± 0.86
#3	WN 7	12.58	1.67	+0.11	1.56	2.84 ± 0.48	-5.92 ± 0.8	15.93 ± 0.93
#4	O9.5 I	11.92	1.55	−0.09	1.64	2.98 ± 0.5	-5.7 ± 0.5	14.64 ± 0.71
#7	B0–B1 I	11.87	1.55	−0.08	1.63	2.97 ± 0.49	-6.0 ± 0.8	14.90 ± 0.94
#11	B0 I	11.90	1.63	−0.08	1.71	3.11 ± 0.52	-5.85 ± 0.5	14.64 ± 0.72
B	WC 9d	10.40	3.03	+1.10	1.93			
C	B1–B3 I	10.96	1.81	−0.08	1.89	3.43 ± 0.57	-6.50 ± 0.8	13.88 ± 0.98
D	OB I	11.06	1.69	−0.09	1.78			
Average						3.00 ± 0.3		14.69 ± 0.35

Table 3. Ages and progenitor masses ($M^{\rm OB}_{\rm init}$) of #4 (O9.5 I) and #11 (B0 I) from Lejeune & Schaerer (2001) isochrones using Meynet et al. (1994) evolutionary tracks for a variety of DM plus inferred minimum magnetar progenitor masses ($M^{\rm SGR}_{\rm init}$).

DM (mag)	d (kpc)	Star	$M_{K_{\rm s}}$ (mag)	$M_{\rm Bol}$ (mag)	Log T (K)	Age (Myr)	$M^{\rm OB}_{\rm init}$ (M$_\odot$)	$M^{\rm SGR}_{\rm init}$ (M$_\odot$)
14.0	6.3	#4	−5.1	−8.5	4.46	5	30	35
		#11	−5.2	−8.5	4.44		30	35
14.3	7.2	#4	−5.4	−8.8	4.46	4.6	33	40
		#11	−5.5	−8.8	4.44		33	40
14.7	8.7	#4	−5.8	−9.2	4.46	4	40	48
		#11	−5.9	−9.2	4.44		40	48
15.1	10.5	#4	−6.2	−9.6	4.46	3.4	49	69
		#11	−6.2	−9.6	4.44		49	69
15.4	12	#4	−6.5	−9.9	4.46	3	55	100
		#11	−6.6	−9.9	4.44		55	100
15.9	15	#4	−7.0	−10.4	4.46	2.8	80	120
		#11	−7.1	−10.4	4.44		80	120

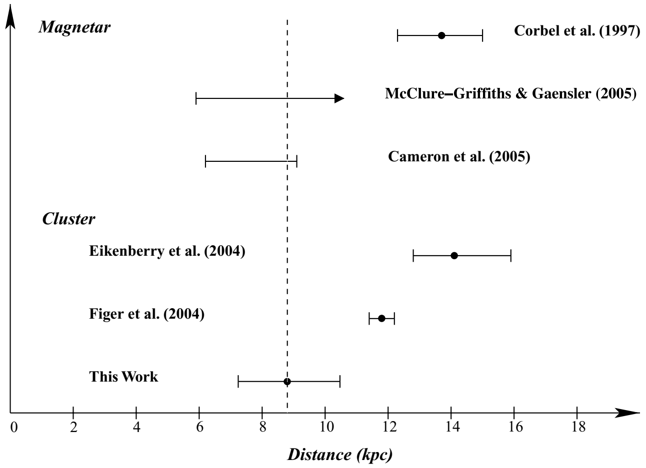

Figure 4. Comparison of present results for the distance to the 1806−20 cluster with previous cluster and magnetar distance estimates, adapted to a Galactic Centre distance of 8 kpc (Reid 1993).

conclusions were reached by Figer et al. (2005). The observed association between magnetars and supernova remnants suggests that magnetars are young neutron stars ($\leqslant 10^4$ yr; Gaensler et al. 2001), so the actual progenitor mass ought to be close to the values listed in Table 3. Following the approach of Figer et al. (2004), we estimate a mass of ∼36 M$_\odot$ for LBV 1806−20 based on our revised distance, assuming it is a binary with equal mass components.

This distance represents a major downward revision to the current adopted magnetar distance of 15 kpc, suggesting a peak luminosity of $\sim 7 \times 10^{46}$ erg s^{-1} for the 2004 December giant flare. Hurley et al. (2005) argue that up to 40 per cent of all BATSE short GRBs could be giant flares from magnetars, if one was to adopt a 15 kpc distance to SGR 1806−20 and a frequency of giant flares of one per 30 yr per Milky Way galaxy. For the revised distance, perhaps only ∼8 per cent of BATSE short GRBs have an origin in magnetar giant flares (see Popov & Stern 2006).

Our preferred distance of $\sim 8.7^{+1.8}_{-1.5}$ kpc to the 1806−20 cluster suggests active star formation at a distance of $1.6^{+1.4}_{-0.1}$ kpc from the centre of the Milky Way. It is well known that the amount of molecular hydrogen is greatly reduced interior to the bar at ∼4 kpc (Benjamin et al. 2005) causing a deficiency in H II regions (Russeil 2003) in the inner Milky Way, apart from the Galactic Centre region itself. Apparently relatively massive clusters can form within this region. From the current massive star census, a cluster mass in excess of $\sim 3 \times 10^3$ M$_\odot$ is estimated from comparison with the Quintuplet cluster, albeit based upon highly incomplete statistics. Further spectroscopic studies of the 1806−20 cluster are recommended to further refine the distance and detailed stellar content.

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