SCP 06F6: A CARBON-RICH EXTRAGALACTIC TRANSIENT AT REDSHIFT z \approx 0.14?

BORIS T. GÄNSICKE, ANDREW J. LEVAN, THOMAS R. MARSH, AND PETER J. WHEATLEY
Department of Physics, University of Warwick, Coventry CV4 7AL, UK; Boris.Gaensicke@warwick.ac.uk
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ABSTRACT
We show that the spectrum of the unusual transient SCP 06F6 is consistent with emission from a cool, optically thick and carbon-rich atmosphere if the transient is located at a redshift of \( z \approx 0.14 \). The implied extragalactic nature of the transient rules out novae, shell flashes, and V838 Mon-like events as causes of the observed brightening. The distance to SCP 06F6 implies a peak magnitude of \( M_I \approx -18 \), in the regime of supernovae (SNe). While the morphology of the light curve of SCP 06F6 around the peak in brightness resembles the slowly evolving Type IIn supernovae SN 1994Y and SN 2006gy its spectroscopic appearance differs from all previous observed SNe. We further report the detection of an X-ray source coincident with SCP 06F6 in a target of opportunity XMM-Newton observation made during the declining phase of the transient. The X-ray luminosity of \( L_X \approx (5 \pm 1) \times 10^{42} \text{erg s}^{-1} \) is 2 orders of magnitude higher than observed to date from SNe. If related to an SN event, SCP 06F6 may define a new class. An alternative, though less likely, scenario is the tidal disruption of a carbon-rich star.

Key words: stars: individual (SCP 06F6) – supernovae: general

1. INTRODUCTION
Studies of local and distant supernovae (SNe) continue to reveal broad diversity in SN properties, both spectral and photometric. This includes the recognition of SN with extremely high ejecta velocities (hypernovae, e.g., Galama et al. 1998; Mazzali et al. 2002; Hjorth et al. 2003) and those which reach peak magnitudes markedly brighter than seen previously (Smith et al. 2007; Quimby et al. 2007). Indeed, even the “standard candle” SN Ia include examples of unusually discrepant SN, e.g., the extremely faint \( (M_B = -15.9) \) SN 2007ax (Kasliwal et al. 2008). This variety most likely reflects similar variations in progenitor properties such as mass, metallicity, and rotation. Given the dramatically increased rate of SN detection over the past 20 years (there were 20 reported in 1987, 163 in 1997, and 572 in 2007\(^1\)), it is perhaps unsurprising that the classification system has required adaptation. Nonetheless the discovery of SNe whose properties are broadly different from those seen before remains rare, and it is these examples which could perhaps place the strongest constraints on unusual processes in stellar evolution. In fact, from the theoretical perspective, it appears that the full variety of SNe has not been discovered, e.g., Bildsten et al. (2007) suggest the existence of faint \( (M_V = -15 \) to \(-18) \) thermonuclear SNe from helium cataclysmic variables, or the tidal disruption and ignition of a white dwarf by intermediate-mass black holes (Rosswog et al. 2008, 2009).

It is clear that the growing number of large-area imaging surveys with high temporal cadence (hours to days), and the next generation of wide field space-based instruments, will dramatically increase our knowledge about rare transient events. Projects that are currently operating, or coming online in the foreseeable future, span a wide range of aperture sizes, e.g., ASAS (Pojmanski 1997) or SuperWASP (Pollacco et al. 2006) with limiting magnitudes of \( \approx 13-15 \), the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2009) or SkyMapper (Keller et al. 2007) with limiting magnitudes of \( \approx 19-21 \), PanSTARRS (Hodapp et al. 2004) and LSST (Ivezic et al. 2008) with limiting magnitudes of \( \approx 24-25 \), and ultimately SNAP, which may reach \( \approx 28 \) magnitude (Aldering 2005).

\(^{1}\) http://cfa-www.harvard.edu/fau/lists/Supernovae.html

Examples of very unusual events serendipitously discovered by deep SN surveys are a red transient in M85 (possibly the result of a stellar merger (Kulkarni et al. 2007) but see Thompson et al. 2008 for an alternative), and the recent optical transient SCP 06F6 reported by Barbary et al. (2009), which is so far of unknown nature.

Here, we suggest that SCP 06F6 had an extragalactic nature with a redshift of \( z \approx 0.14 \), and may represent a so far unknown type of SN or, less likely, a tidal disruption event.

2. THE UNUSUAL TRANSIENT SCP 06F6
Barbary et al. (2009) discovered the optical transient SCP 06F6 as part of the Hubble Space Telescope Cluster Supernova Survey. The object reached a peak magnitude of \( \approx z_{850} = 21 \), and showed roughly symmetric rise and decay times of \( \approx 60 \) d each. No counterpart is detected down to \( \approx 26.4 \) and \( z_{850} \approx 26.1 \). The optical spectra of SCP 06F6 obtained with Keck and the Very Large Telescope (VLT) were relatively red, peaking at \( \approx 6100 \) Å, and contained several broad absorption troughs bluewards of \( \approx 6500 \) Å. Barbary et al. (2009) discussed the possible nature of SCP 06F6 on the basis of its unusual spectral appearance, but were not able to find any fully convincing solution. In particular, they cross-correlated the spectrum of SCP 06F6 against the spectral database of the Sloan Digital Sky Survey (SDSS), and noted that the best match was found with broad absorption line quasars (BAL QSOs) and carbon-atmosphere (DQ) white dwarfs. The spectra of DQ white dwarfs with temperatures in the range \( \approx 6000-10,000 \) K contain broad absorption bands from \( C_2 \) (Du four et al. 2005; Koester & Knist 2006), also known as Swan bands, which are roughly equally spaced in wavelength. However, Barbary et al. (2009) noted that the positions of these bands in DQ white dwarfs from SDSS did not line up with the absorption features in the spectrum of SCP 06F6. DQ white dwarfs display a rich variety in the general morphology of the Swan bands, however, the position of these absorption troughs remains largely constant (Harris et al. 2003). Furthermore, the spectral energy distribution of DQ white dwarfs is bluer than that of SCP 06F6.
3. A CARBON-RICH OPTICALLY THICK ATMOSPHERE IN SCP 06F6

Upon inspection of the spectrum of SCP 06F6, we noticed a striking resemblance to carbon stars, in particular to several of the faint high-latitude carbon stars presented by Margon et al. (2002). In order to quantify this resemblance, we carried out a spectral template fitting to the spectrum of SCP 06F6.

We obtained the Keck and VLT spectra of SCP 06F6 (Barbary et al. 2009) from the Supernova Cosmology Project Web site. Both spectra were co-added on the wavelength grid of the VLT spectrum to improve the signal-to-noise ratio. We then created a template library from the SDSS spectra of 251 carbon stars identified by Margon et al. (2002) and Downes et al. (2004). The templates were binned to the wavelength grid of the VLT spectrum, and normalized to the spectrum of SCP 06F6 over the range 4000–5500 Å. The quality of the fits was evaluated by calculating $\chi^2$ over the wavelength range 4000–7500 Å, as well as by visual inspection of each fit.

A first run through the template library confirmed the finding of Barbary et al. (2009) that the positions and spacings of the C$_2$ Swan bands do not coincide with the absorption troughs seen in the spectrum SCP 06F6 (Figure 1, top panel).

We then redshifted the carbon star template spectra to adjust the position of their strongest Swan band with the broad absorption feature centered at $\approx$5800 Å in the observations of SCP 06F6. A redshift of $z = 0.143 \pm 0.005$ resulted in good agreement in the wavelengths of all the broad absorption features. The best match in fitting the template library with $z = 0.143$ to the spectrum of SCP 06F6 is found for the carbon star SDSS J001836.23-110138.5, which reproduces the spectral features and the overall spectral shape of SCP 06F6 well (Figure 1, bottom panel).

The presence of C$_2$ in the spectrum of SCP 06F6 implies a relatively low temperature ($\approx$5000–6000 K) of the emitting region, consistent with the red spectral energy distribution. One galactic transient is known that exhibited a spectrum similar to that of SCP 06F6: Sakurai’s Object (V4334 Sgr, Pavlenko et al. 2000). Sakurai’s object was explained as the final helium flash of a hydrogen-deficient post-asymptotic giant branch star, resulting in an optically thick carbon-rich expanding pseudo-photosphere (Duerbeck & Benetti 1996; Herwig 2001). However, the redshift of $z \approx 0.14$ implies that SCP 06F6 reached an absolute magnitude $M_V \sim -18$, which rules out a physical nature similar to Sakurai’s object, for which $M_V > -4$ (Miller Bertolami & Althaus 2007). Similarly, red luminous variables, such as V838 Mon or M31-RedVar ($M_{bol} \sim -10$; Rich et al. 1989), or classical novae ($M_V \sim -9$; Capaccioli et al. 1989) can be excluded.

We conclude that the emission of SCP 06F6 observed during peak brightness originated in a cool, optically thick and carbon-rich atmosphere. We stress, however, that this morphological result does not imply that the progenitor was a normal carbon star—just as the progenitor of Sakurai’s object was not a carbon star.

4. X-RAY DETECTION OF SCP 06F6

In addition to the optical observations reported in Barbary et al. (2009), we have also examined a target of opportunity XMM-Newton observation of SCP 06F6 made on 2006 August 2 during the declining phase of the transient’s light curve. The 15 ks observation was severely affected by a high radiation background, which forced premature ends to the exposures with the EPIC cameras. The resulting images have high background levels and exposure times of 10, 8, and 3 ks, respectively in the MOS1, MOS2, and PN cameras. An X-ray source is clearly detected in the soft X-ray images of both EPIC MOS cameras, and within the positional error the location of the X-ray source is consistent with that of SCP 06F6 (Figure 2). The MOS1 count rate for this source in the 0.2–2.0 keV band is 0.0138 $\pm$ 0.0038 s$^{-1}$, corresponding to a flux of $1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the same band. At a redshift of $z = 0.143$ this would correspond to an X-ray luminosity of $L_X = (5 \pm 1) \times 10^{42}$ erg s$^{-1}$.

The position of SCP 06F6 has also been observed at two epochs with the Chandra X-ray observatory, once before the transient (2003 April 1) and once after the XMM-Newton.

![Figure 1. Top panel: the spectrum of SCP 06F6 (thin black line, co-added from the Keck and VLT data of Barbary et al. 2009) and the SDSS spectrum of the carbon star SDSS J001836.23-110138.5 (Downes et al. 2004). While the spectral energy distributions of the two spectra are similar, the positions of the C$_2$ Swan bands totally disagree. Bottom panel: same as before, but the spectrum of the carbon star has been redshifted to $z = 0.143$, which brings the positions of the Swan bands in agreement with the absorption troughs seen in SCP 06F6. Shown as a thin gray line offset by 2.6 flux units is the carbon star spectrum convolved with a 4000 km s$^{-1}$ outflow velocity profile. This illustrates that an expanding envelope will smooth out to some extent the sharp C$_2$ band-heads.](image1)

![Figure 2. X-ray images of SCP 06F6 in the energy range 0.2–2.0 keV taken simultaneously with the two EPIC MOS instruments on XMM-Newton (left: MOS1, right: MOS2). Inset panels show the expected source position (marked with a cross) and the 1σ error on the detected X-ray source position, adopting the mean uncertainty for faint sources in the 2XMM catalog (Watson et al. 2009).](image2)
pointing (2006 November 4). No source is detected at the position of SCP 06F6 at either epoch. A flux upper limit of 7.8 × 10⁻¹⁵ erg s⁻¹ cm⁻² in the 0.5–7.0 keV band is reported by Barbary et al. (2009) for the first epoch. We have examined the 5 ks observation from the second epoch and derive a 99% confidence upper limit to the count rate of 0.00084 s⁻¹, corresponding to a robust flux upper limit of 1 × 10⁻¹⁴ erg s⁻¹ cm⁻² in the 0.5–7.0 keV band. For all reasonable thermal and non-thermal model spectra, the flux in the 0.2–2.0 keV band must be below 6 × 10⁻¹⁵ erg s⁻¹ cm⁻².

We conclude that the XMM-Newton X-ray detection of SCP 06F6 is associated with the transient outburst, and that the X-ray luminosity of this object must have increased and then declined again by at least an order of magnitude with respect to any quiescent emission.

5. DISCUSSION

In the two previous sections, we concluded that the morphology of the optical spectrum of SCP 06F6 at maximum brightness indicates an origin in a cool, optically thick and carbon-rich atmosphere at a redshift of ∼0.14, and that the optical transient was accompanied by a luminous X-ray transient. Here, we discuss the implications for the nature of SCP 06F6.

The symmetric light curve of SCP 06F6 prompted Barbary et al. (2009) to consider microlensing as an explanation, although, as they pointed out, the large minimum amplification (>120) and the ~100 day timescale are hard to understand on such a hypothesis. It can be added that the light curve does not have the extended wings of microlensing light curves. If our identification of Swan bands is correct, then the microlensing hypothesis seems even more implausible. If microlensing was the cause, then the source would be a carbon star at z ∼ 0.14 (dismissing the unlikely combination of a new type of cool transient and microlensing). The brightest carbon stars have absolute magnitudes around −4 (Rebeirot et al. 1993), and so microlensing would have to provide at least 14 mag or a factor of 400,000 amplification. Roughly the right timescale and amplification result from a 5 M☉ object, placed half-way to the carbon star, passing within 4 AU of the line of sight to the carbon star at a transverse speed of 200 km s⁻¹. However, the configuration is highly contrived, and requires the host galaxies of both the carbon star and lensing object to be unusually faint (see below). The problem of two faint galaxies can be avoided if the lensing object is located in either our galaxy or equivalently the host galaxy of the carbon star, but then the lensing object has to be very massive (several hundred solar masses). We therefore reject microlensing as playing any role in explaining SCP 06F6.

We suggest as a possible scenario that SCP 06F6 is related to a SN-like event of a carbon-rich star. The peak magnitude of SCP 06F6 is comparable to the peak in the luminosity function of core collapse SNe. The implied light curve is shown in Figure 3, where it is compared to several other SNe. As noted by Barbary et al. (2009) the transient is very slow in comparison to the majority of SNe, which reach their peak on timescales of ~30 days or less. However, some SNe, such as the II-n SN 1994y (Ho et al. 2001) and SN 2006gy (Smith et al. 2007), do appear to have broad peaks, albeit with poor sampling of the rise. Overall the ensemble of SN light curves seems to broadly incorporate that of SCP 06F6. If SCP 06F6 is related to SNe, it will involve a rapid expansion of the envelope. For a peak magnitude M_I = −18, an assumed temperature of 5000 K, and a redshift of z = 0.14, the radius of SCP 06F6 would be ∼3.5 × 10¹⁰ km. Assuming further that the expansion to this dimension occurred over ∼100 days, an expansion velocity of ~4000 km s⁻¹ is implied. Given the already broad nature of the C₂ Swan bands, the velocity gradient across the visible fraction of the envelope would result only in a relatively mild broadening, that would not distort the general appearance of the spectral features, but would just somewhat smooth out the sharp Swan band-heads seen in carbon stars.

A puzzling aspect should SCP 06F6 lie at moderate redshift is the absence of an apparent host galaxy. The nearest detected object to the location of SCP 06F6 is a 6σ detection of an object with zₘ₉₀ = 25.8, 1.5 arcsec from the transient position. At redshift z ∼ 0.14 this corresponds to an absolute magnitude of M_z ∼ −13.2, which is extremely faint. Only a small proportion of stars lie in such low-mass galaxies, although examples of star-forming galaxies with comparable absolute magnitude (e.g., IC 1613; Dolphin et al. 2001) can be found. A number of SNe and GRBs have occurred in faint (M_R ≥ −13) galaxies (e.g., Levan et al. 2005; Fruchter et al. 2006; Drake et al. 2009), indicating that such an association is not impossible. The presence of C₂ Swan bands in the spectrum of SCP 06F6 requires a carbon to oxygen ratio of CO > 1 by number, such that the carbon is not locked up in CO, favoring regions of low metallicity where it is easier for a small amount of carbon production to overwhelm the oxygen abundance. Given the well-known relation between mass (or luminosity) and metallicity (Tremonti et al. 2004), such carbon-rich events may preferentially occur in faint host galaxies. Deep spectroscopy of the hypothetical nearby galaxy may enable a measure of its redshift, to test the association with SCP 06F6 if at z ∼ 0.14. The X-ray luminosity of SCP 06F6 inferred from the
XMM-Newton observations, $L_X = (5 \pm 1) \times 10^{42} \text{ erg s}^{-1}$, is much larger than expected from normal core collapse SNe (Uno et al. 2002; Kouveliotou et al. 2004), though the SN IIn 1988Z and 2006jd reached $L_X \simeq 1-2.5 \times 10^{41} \text{ erg s}^{-1}$ (Fabian & Terlevich 1996; Immler et al. 2007). It is intriguing that both the slowly evolving light curve and large X-ray luminosity of SCP 06F6 bear similarities to the behaviors observed in SN IIn, despite the radically different spectral appearance. A speculative scenario is that SCP 06F6 is associated with the death of a massive star that underwent mass loss removing the hydrogen envelope, e.g., a WC Wolf–Rayet star prior to the explosion, creating a carbon-rich circumstellar environment, or a Iben & Renzini type 1.5 SN inside a metal-poor AGB star (Zijlstra 2004), which might possess a carbon-rich envelope at the point of core ignition. Interaction of the reverse shock with dense circumstellar matter would then also provide an explanation for the X-ray emission of SCP 06F6 (Chevalier & Fransson 1994). We note in passing that Thompson et al. (2008) related the luminous transients SN 2008S and NGC 300 to either core-collapse SNe or bright eruptions of massive dust-enshrouded stars, possibly carbon stars.

An alternative hypothesis of SCP 06F6 is that it is not due to stellar collapse but rather to the tidal disruption of a carbon rich star by a black hole. Such tidal disruption events may occur in the core of normal galaxies when stars approach the central black hole (Rees 1988); or further out in hosts via intermediate-mass black holes (e.g., Rosswog et al. 2009). These events can potentially create the light-curve shape (long duration flare) and approximate luminosity seen in SCP 06F6, for example, object D3-3 in Gezari et al. (2008) reaches a peak magnitude of $M_K \sim -19$ and has a transient duration of several hundred days. The X-ray luminosity of SCP 06F6 is comparable to that of the candidate tidal disruption events identified in the XMM-Newton Slew Survey (Esquej et al. 2007). This interpretation has the advantage that it more naturally explains the X-ray luminosity in tandem with that in the optical. Finally, tidal disruption events may lead to the ejection of a large fraction of the material of the disrupted star (Ayal et al. 2000), explaining the presence of a large optically thick envelope.

However, this interpretation is not without problems. The lack of any obvious host galaxy to very low luminosities would imply either a very low black hole mass (if black holes do exist at the centers of dwarf irregulars) or that the black hole has somehow been ejected from its host (as has been suggested in a few cases, e.g., Magain et al. 2005; Haehnelt et al. 2006). These possibilities, combined with the observation that the disrupted object be a carbon-rich star, rather than a normal main sequence one appear to make the case for tidal disruption somewhat contrived. Nonetheless, with only one object, and thus an essentially unconstrained rate and space density for such events, it remains a possibility.

Any model of this source will need to explain both its unusual spectral appearance and the implied abundances as well as the high X-ray luminosity.

6. SUMMARY

We have suggested that the unusual transient recently reported by Barbary et al. (2009), can be interpreted as being due to a carbon-rich SN-like event. We identify the features in the optical spectrum of SCP 06F6 as being due to carbon Swan bands, at a redshift of $z \simeq 0.14$. At this redshift the energetics of SCP 06F6 resemble those of core-collapse SNe, albeit with a longer than typical rise time, and higher than typical X-ray luminosity. If correct, this suggests that the rare collapse of carbon-rich stars can yield SNe very different from the bulk populations which are frequently observed in current transient searches, and further motivates the next generation of transient experiments.

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