HUNTING FOR THE PROGENITOR OF SN 1006: HIGH-RESOLUTION SPECTROSCOPIC SEARCH WITH THE FLAMES INSTRUMENT

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ABSTRACT

Type Ia supernovae play a significant role in the evolution of the universe and have a wide range of applications. It is widely believed that these events are the thermonuclear explosions of carbon–oxygen white dwarfs close to the Chandrasekhar mass (1.38 \( M_\odot \)). However, CO white dwarfs are born with masses much below the Chandrasekhar limit and thus require mass accretion to become Type Ia supernovae. There are two main scenarios for accretion: first, the merger of two white dwarfs and, second, a stable mass accretion from a companion star. According to predictions, this companion star (also referred to as donor star) survives the explosion and thus should be visible in the center of Type Ia remnants. In this paper, we scrutinize the central stars (79 in total) of the SN 1006 remnant to search for the surviving donor star as predicted by this scenario. We find no star consistent with the traditional accretion scenario in SN 1006.

Key words: binaries: symbiotic -- stars: abundances -- supernovae: individual (SN 1006)

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have applications in a wide range of astronomical fields. Their iconic use as cosmological distance probes which enabled the discovery of the accelerated expansion of the universe is augmented by their role as major drivers of chemical evolution in the universe. They are also physically interesting endpoints of stellar evolution. It is therefore an embarrassment that the progenitors of these explosions are as yet unknown.

The spectra and light curves of SNe Ia suggest that the explosion is powered by burning of degenerate carbon-rich matter, suggesting carbon/oxygen white dwarfs as progenitors of SN Ia. These objects provide carbon-rich degenerate matter and self ignite as they approach the Chandrasekhar mass threshold (1.38 \( M_\odot \)). Most white dwarfs, however, are born with masses much below the Chandrasekhar limit and how they reach the required threshold is as of yet unknown. Two main scenarios have been identified by the community (Iben 1997). The first channel involves the merger of two white dwarfs (double-degenerate scenario, DD-scenario) with a total mass above the Chandrasekhar limit and explosive nucleosynthesis of the merger product. In the second channel, mass is accreted from a non-degenerate companion (single-degenerate scenario, SD-scenario). Close to the Chandrasekhar limit, explosive carbon burning ensues and the white dwarf undergoes a thermonuclear detonation/deflagration. This scenario offers an important calling card: the survival of the non-degenerate companion (also known as donor star).

Our lack of understanding about the progenitor channel has significant impact on our understanding of the chemical evolution of the universe. Thus, the community has put considerable effort into uncovering the progenitor scenario (Ruiz-Lapuente et al. 2004; González Hernández et al. 2009; Kerzendorf et al. 2009; Schaefer & Pagnotta 2012, for a review see Kerzendorf et al. 2012). A direct detection of a surviving donor star in a Galactic Type Ia remnant would substantiate the single-degenerate channel for at least one system.

The community has identified several Galactic Type Ia remnants that lend themselves to the search for the surviving donor star (RCW86, SN 1006, SN 1572, and SN 1604). In this paper, we have chosen SN 1006 for a spectroscopic search of the inner stars. The lack of a central neutron star, observations of several tenths of a solar mass of iron inside the remnant (Hamilton et al. 1997), the high peak luminosity, and basic light curve shape (visible for several years; Goldstein & Peng Yoke 1965) all indicate that SN 1006 was an SN Ia. The remnant has a secure distance, measured by Winkler et al. (2003), who combined the proper motion and the radial velocity of the expanding shell to measure the distance to 2.2 kpc, making SN 1006 the closest of the Galactic SN Ia remnants (consistent with SN 1006 being the brightest). The geometric center of the remnant is well determined from both X-ray and radio observations (Winkler et al. 2003).

The interior of the remnant has been probed with UV background sources (Winkler et al. 2005), which revealed the aforementioned iron core as well as a silicon-rich shell (adding to the evidence that SN 1006 was an SN Ia event). In addition, the remnant has been searched previously for possible objects associated with the supernova explosion, which revealed an unusual O-star (Schweizer–Middleditch Star, henceforth SM-Star; Schweizer & Middleditch 1980) that was suggested to be a possible remnant star to SN 1006. After successful identifications of neutron stars in both the Vela Remnant and the Crab Remnant this was thought to be the third identification of a stellar remnant in a historical supernova. Subsequent UV spectroscopic follow-up of the Schweizer–Middleditch star (SM-Star) by Wu et al. (1983) showed strong Fe ii lines with a profile broadened by a few thousand km s \(^{-1}\) and symmetrically distributed around the rest-wavelength. In addition, Wu et al.
(1983) identified redshifted Si iv lines. Their conclusion was that these absorption lines stem from the remnant and place the SM-Star behind the remnant, making it unrelated to SN 1006. The SM-Star remains an ideal object to probe the remnant and measure upper limits for interstellar extinction $E(B - V) = 0.1$ (Wu et al. 1993; Winkler et al. 2003).

SN 1006 has several properties that make it well suited for a progenitor search. Although the remnant is the oldest among the remnants with a secure Type Ia identity, its age is still young enough that the remnant’s center is well determined, and the motion of any potential donor star is low enough that only a small area needs to be searched. Furthermore, the elapsed time of 1005 years is a short length of time relative to the timescales of stellar evolution for donor stars (see Marietta et al. 2000) so we still expect a potential donor star to be close to the same state as directly after the supernova explosion. In addition, SN 1006 has a low interstellar extinction, which eases the determination of stellar parameters. Finally, with 2.2 kpc it is the closest of the known SN Ia remnants and thus is suitable for a relatively deep survey. These serendipitous conditions for the SN 1006 remnant led us to launch a photometric and spectroscopic campaign to search for the donor star.

In Section 2, we outline the observations as well as data reduction of the photometric and spectroscopic data. Section 3 is split into three subsections, namely, radial velocity, stellar rotation, and stellar parameters. We discuss our findings in Section 4 and conclude our work in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Photometric Observations

CCD images of the central 6′ of the SN 1006 remnant were obtained using the imaging camera at the Nasmyth-B focus of the ANU 2.3 m Telescope at the Siding Spring Observatory on 2004 May 11. The camera has a 6′ diameter circular field with a scale of 0′′.375 pixel$^{-1}$. We used the broadband Bessell $UBVI$ filters and exposed for 1860 s in $U$, 1490 s in $B$, 788 s in $V$, and 1860 s in $I$. For calibration purposes we took images of the PG1633 and PG1047 standard star regions (Landolt 1992) in the same filters. The seeing ranged between 1″ and 2″, and the conditions were photometric. The data were bias corrected and flat-fielded (with skyflats) using PyRAF5 and IRAF6.

For our photometric data reduction we fitted an astrometric solution using the astrometry from the Two Micron All Sky Survey (2MASS) point-source catalog (Skrutskie et al. 2006) to our frames. We used SExtractor (Bertin & Arnouts 1996) to measure the magnitudes of the objects in the frames (using a 2″ aperture), corrected for atmospheric extinction, and then we calibrated our photometry to the standard Johnson–Cousins $UBV(Ic)$ system using the Stetson magnitudes of the stars in the standard fields PG1633+099 and PG1047+003 (Landolt 2009). The measured magnitudes were supplemented with near-infrared magnitudes from the 2MASS point-source catalog (see online tables).

5 PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.
6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF).

We have also computed temperatures from photometric colors by using the polynomials given in Casagrande et al. (2010). In the first instance, we assumed a solar metallicity for all stars, but the choice of metallicity only has a relatively minor influence on the temperature determination, for example, using $B - V$ there is a change of less than 200 K for metallicities between $[Fe/H] = 0$ and $[Fe/H] = -1$, while for $V - K$ and $V - I$ there is virtually no change. All temperatures are provided in online tables.

2.2. Spectroscopic Observations

For the spectroscopy survey we used the Very Large Telescope instrument FLAMES, which can provide high-resolution ($R = 25,000$) optical spectra over a 25′′ field of view for up to 130 objects. In this mode, the spectral coverage is limited to 200 Å. We chose the wavelength region from 5139 Å to 5356 Å which contains the gravity sensitive Mg b triplet as well as many iron lines, to accurately measure metallicity. For the center of our spectroscopic survey we chose the mean of the X-ray and radio center ($α = 15^h02^m22^s1 δ = -42^o05′49″$; Winkler et al. 2003). We do note that the center choice is one of the most challenging choices in a progenitor search. Particularly, measurements by Winkler et al. (2005) cast doubt on a precise determination of the center of SN 1006. Their research suggests that the center of the iron core is offset from the geometric center determined by the shocked interstellar medium. However, we argue that this does not mean that the center of mass (where a donor star would reside) is necessarily off-center. In fact, Maeda et al. (2010) suggest that the iron ejecta is offset from the center of mass, which suggests that the center of the iron core will be different from the center of mass. In general, explosion models are consistent with the center of mass being given by the outer shock, not the iron core. In addition, we chose a generous search radius of 120′′, corresponding to the motion of a star traveling 1250 km s$^{-1}$ at 2.2 kpc over 1000 years. This choice, which is more than four times the maximum expected escape velocity of the donor from the system (Han 2008), was made to accommodate any errors in the choice of the center. Although the models predict the surviving companion to be several hundred L$_⊙$ (Marietta et al. 2000), we chose a limiting magnitude of $V = 17.5$ (0.5 L$_⊙$(V) at 2.2 kpc including reddening $E(B - V) = 0.1$; see Equation (1)) to accommodate a wide range of potential donor star scenarios.

$$L_⊙(V) = 10^{-(0.4(V - 3.83)+1.24E(B - V)) - 4.8 \cdot 10^4 \left( \frac{d}{2.2 \text{ kpc}} \right)^2}, \; (1)$$

An exposure time of 3.8 hr was chosen to obtain spectra with high enough quality to measure rotation and basic stellar parameters (signal-to-noise ratio >20). For completeness and so as not to waste fibers we chose additional stars down to a magnitude limit of $V = 19$ only to be used for radial velocity measurements. There are 26 stars with $V < 17.5$ and 53 stars with 17.5 mag $< V < 19$ mag (for a total of 79 stars) for our survey (see Figure 1). With fiber buttons not being able to be placed less than 11″ apart, we had to split our candidates over three different setups. The first two setups were observed five times for 2775 s each time. We deliberately chose bright stars for the last setup so that it only had to be observed three times for 2775 s each time. In addition, we placed spare fibers on three bright stars ($R \approx 10$; 2MASS J15032744-4204463, 2MASS J15031746-4204165, 2MASS J15033195-4202356) located close to the edge of the 25′′ field of view for calibration purposes. Additional spare fibers were placed.
on sky positions, which were chosen to be far from 2MASS sources and manually inspected on DSS images to be in star-free regions. In addition to our nighttime calibration, which included simultaneous arc exposures with four fibers for each observation block, we received standard daytime calibrations. In total, 13 observation blocks with an exposure time of 2775 s each were obtained. Table 1 provides the observing ID, modified Julian date, mean seeing, mean airmass, setup name, and heliocentric correction for all observations (all data are available under ESO Program ID: 083.D-0805(A)). Due to broken fibers, not all stars...
were observed for the expected length of time. Broken fibers caused SN1006-31 not to be observed at all in this project (see Figure 2), although with $V = 17.87$, SN1006-31 is not part of our primary sample and thus not crucial for our search.

We first applied a cosmic ray removal tool on the raw two-dimensional frames (van Dokkum 2001). The data were then reduced with the ESO-CPL pipeline (version 5.2.0), using the GIRAFFE instrument recipes (version 2.8.9). The only variation that was made to the default parameters was the usage of the Horne extraction algorithm instead of the “Optimal” extraction algorithm. This yielded 366 individual spectra of the candidate stars and an additional 39 calibration star spectra.

3. ANALYSIS

3.1. Radial Velocity

To obtain radial velocities we employ a two-step process. We first cross correlated each spectrum with a solar spectrum from Kurucz et al. (1984) using the standard technique described in Tonry & Davis (1979) and implemented in the PyRAF task fxcor. The cross-correlation was performed on each individual spectrum. In the second step, heliocentric corrections were applied, and then the results were averaged for each star with a sigma clipping algorithm (for candidate stars with $V < 17.5$, see Table 2; the radial velocities of all stars are available online). We note that especially for faint objects we observe a second cross-correlation peak at 0 km s$^{-1}$ and suspect that this stems from scattered moonlight. We believe that this has a negligible effect on our radial velocity measurement. In Figure 3, we compared our radial velocity measurements with the Besançon kinematic model of the Milky Way (Robin et al. 2003). Our selection criteria from the Besançon kinematic model was all stars within 1 deg$^2$ of SN 1006 and a magnitude cut of $10 < V < 17.5$. We compared the resulting 10,000 stars to our 78 stars in the sample in Figure 3. All stars are consistent with what is expected from the Besançon model and show no irregularities attributable to donor star candidates.

3.2. Rotational Velocity

Kerzendorf et al. (2009) suggest that a previously unrealized feature of donor stars is high rotation. Contrary to the predicted radial velocity signature which can be submerged in the velocity distribution of the Galaxy, the rotational velocities of stars are normally less than 10 km s$^{-1}$ for late-type stars and the predicted high rotational velocities of donor stars should be clearly distinguishable. The measured rotational velocity includes a factor of sin$i$. However, the expected rotational velocities are above $v_{\text{rot}} = 50$ km s$^{-1}$ and thus we still expect to see modest rotation even with a high inclination angle.

We have measured the rotational velocity of the stars of the $V < 17.5$ candidate stars using a cross-correlation technique (Carney et al. 1987). First, we cross-correlated the stars with a
synthetic spectrum matching closest in $T_{\text{eff}}$, $\log g$, and [Fe/H] space (and an intrinsic rotational velocity of $v_{\text{rot}} = 2$ km s$^{-1}$). If the cross-correlation peak was broader than expected from instrumental resolution ($\approx 12$ km s$^{-1}$), we attributed the extra broadening to rotation. This should yield the qualitatively correct result, although there may be significant systematic errors (due to other broadening effects, however <5 km s$^{-1}$). However, our main goal is to identify rotators with $v_{\text{rot}} > 30$ km s$^{-1}$, which this technique does with a high degree of confidence. The resulting estimates of $v_{\text{rot}} \sin i$ are given in Table 2.

### 3.3. Stellar Parameters

We obtained detailed stellar parameters for the donor candidates with $V < 17.5$ by employing a grid-based technique with a three-dimensional grid in $T_{\text{eff}}$, $\log g$ and [Fe/H]. Moog (Snedden 1973) was used to synthesize the spectral grid using the model stellar atmospheres by Castelli & Kurucz (2003). Line wings were taken into account up to 8 Å away from the line center, which seemed to be a reasonable compromise between grid creation time and accuracy. For the atomic lines, we merged values from the Vienna Atomic Line Database (Kupka et al. 2000) with adjusted values (to reproduce the Arcturus and the Sun) from Gustafsson et al. (2008). In addition, we used the measured molecular lines described in Kurucz & Bell (1995). The final grid extends from 3500 K to 7500 K in effective temperature with a step size of 250 K, from 0 to 5 in surface gravity with a step size of 0.5, from $-2.5$ to 0.5 in [Fe/H] with a step size of 0.5 (with an extra set of points at 0.2).

We used the appropriate sections from the solar spectrum (Kurucz et al. 1984) and the Arcturus spectrum (Hinkle et al. 2000) to calibrate our spectral grid. We measured stellar parameters by first finding the best-fitting grid point and then using the minimizer minuit to find a minimum by interpolating between the grid points (Barber et al. 1996). For the Sun we obtain stellar parameters of $T_{\text{eff}} = 5825$ K, $\log g = 4.4$, and [Fe/H] = $-0.12$ and for Arcturus we obtain stellar parameters of $T_{\text{eff}} = 4336$ K, $\log g = 1.9$, and [Fe/H] = $-0.67$ (cf. $T_{\text{eff}} = 4436$ K, $\log g = 1.84$, [Fe/H] = $-0.54$; Luck & Heiter 2007). We acknowledge the error in measurement, but believe our spectral grid to be accurate enough for distinguishing a potential donor candidate against an unrelated star (our requirement is to determine log $g$ to 1 dex and $T_{\text{eff}}$ to 1000 K accuracy).

To fit our observed spectra, we first fitted the continuum with Legendre polynomials with a maximum order of three and a sigma clipping algorithm to discard the lines. The order that gave the lowest rms of the fit was adopted. We then combined the spectra using the previously measured radial velocity and the computed heliocentric correction. In addition, we broadened the synthetic spectral grid with a rotational kernel for each star where applicable. These spectra were then fitted using the previously described algorithm, except that we added the $B-V$ photometric temperature as a prior. As the photometric temperature uses the metallicity as an input parameter we recalculated the photometric temperature prior to using the metallicity determined by the fit. This procedure was repeated until the gravity estimate converged to less than 0.1 dex. We believe our temperatures to be good to a few hundred Kelvin, and our surface gravities and metallicities have a systematic uncertainty of roughly 0.5 dex (much smaller than our required precision).

The stellar parameters are given in Table 2. The final set of stellar parameters shows a typical distribution of many dwarfs and a few giants. None of the stars seem to be unusual in any way.

### 4. DISCUSSION

In this work we have scrutinized all stars to a limit of $0.5 \, L_\odot (V)$ at the distance of the SN 1006 remnant. In addition, we have performed radial velocity measurements of stars down to a limit of $\approx 0.1 \, L_\odot (V)$ at the distance of SN 1006. Although theoretical models predicted bright donor stars, we have searched down to relatively faint limits. As these predictions were only theoretical in their nature, it was important to establish further features that could hint at a donor star (namely, rotation, radial velocity, and unusual stellar parameters). We used population synthesis models from Han (2008) to judge our rotation measurement with the rotation of donor stars post-explosion (see Figure 4). None of the stars scrutinized in our sample show features consistent with those expected in any current donor star models or are significantly unusual.

Giant donor stars are easily ruled out because there is no star bright enough to be at the distance of the remnant. Marietta et al. (2000) suggest that giant donors have a luminosity of $\approx 1000 \, L_\odot (V) (\approx 9$ at the distance of the remnant) for at least 100,000 years. Furthermore, these models suggest that the giant donor is likely to have a high temperature of more than $10^4$ K. In addition, the star should have rotation in excess of what has been measured for any of the stars in this sample. In summary, there is no viable giant star donor star among the stars located in SN 1006.

Subgiant donors should also be very luminous post-explosion (Marietta et al. 2000) with a minimum expected luminosity of $L \approx 500 \, L_\odot (V \approx 9.7$ at the distance of the remnant) lasting for 1400–11,000 years, although theoretical models allow a much larger variation of this class of stars (Podsiadlowski 2003). While they might have a radial velocity which could be masked by the large expected dispersion in the direction of SN 1006,
the expected $v_{\text{rot}} \approx 80 \text{ km s}^{-1}$ (see Figure 4) far exceeds any star in our sample. Therefore, we believe we can confidently rule out subgiant donor stars in this case as well. In summary our research shows a consistent result to SN 1572—there is no identifiable donor star for SN 1006.

Finally, main-sequence stars, according to Marietta et al. (2000) are expected to have a similar brightness to subgiant stars, although this enhanced luminosity depends on the details of how energy is deposited from the explosion (see Podsiadlowski 2003). However, main-sequence donors should have both substantial spatial motion and a very high rotation. No star in our sample shows any of these features and our sample’s depth should cover all conceivable post-evolutionary scenarios, even for a main-sequence donor star.

One caveat is that rotation can decrease due to expansion (Kerzendorf et al. 2009). However, this should result in a star with a low gravity. No such star is present in SNR 1006.

5. CONCLUSIONS

The observations presented here for SN 1006 are in conflict with the standard SN Ia donor star scenarios, which include accretion onto a white dwarf from a main sequence, subgiant, or giant companion.

A complementary study to this one by González Hernández et al. (2012) that covers a wider but shallower area around SN 1006 has also failed to find a viable candidate.

A few non-standard scenarios survive our observational tests. These include a helium white dwarf as a donor star, which would not be detectable with our observations, although it is not entirely clear that a helium white dwarf would survive the explosion (R. Pakmor 2011, private communication). In addition, Justham (2011) & Di Stefano et al. (2011) suggest that the donor star might evolve and become a white dwarf before the supernova explosion. The delay in explosion is explained by the need to spin down to reach critical density in the core of the white dwarf. This would again result in a companion, which is not detectable by our methods. Finally, another possibility is that SNe Ia (or at least SN 1006) do not have donor stars, consistent with a DD-scenario.

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