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# The Schweizer–Middleditch star revisited

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**Abstract.** We have re-observed and re-analysed the optical spectrum of the Schweizer–Middleditch star, a hot subdwarf which lies along almost the same line-of-sight as the centre of the historic SN1006 supernova remnant (SNR). Although this object is itself unlikely to be the remnant of the star which exploded in 1006AD, Wellstein et al. (1999) have demonstrated that it could be the remnant of the donor star in a pre-supernova Type Ia interacting binary, if it possesses an unusually low mass. We show that, if it had a mass of $0.1-0.2\ \mathrm{M}_{\odot}$, the SM star would lie at the same distance (≈800pc) as the SNR as estimated by Willingale et al. (1995). However, most distance estimates to SN1006 are much larger than this, and there are other convincing arguments to suggest that the SM star lies behind this SNR. Assuming the canonical subdwarf mass of $0.5\ \mathrm{M}_{\odot}$, we constrain the distance of the SM star as 1050 pc<d<2100 pc. This places the upper limit on the distance of SN1006 at 2.1 kpc.

**Key words:** stars: supernovae: individual: SN 1006

## 1. Introduction

SN 1006 was the brightest supernova witnessed in recorded history. The estimated peak magnitude (V=−9.5±1, Clark & Stephenson 1977), reported visibility for nearly two years, and the lack of a nearby OB association strongly suggests a Type Ia origin (SNIa, Minkowski 1966). Almost all current models of Type Ia supernova involve the nuclear explosion of a white dwarf induced by rapid mass accretion in a binary system. However, no stellar remnant from this supernova explosion has ever been conclusively identified, including a pulsar, or the remains of any companion star.

In 1980, Schweizer & Middleditch searched for just such a stellar remnant from SN 1006 and discovered a faint (V=16.7) blue star ≈2.5' from the projected centre of the supernova remnant (SNR). They identified this object (now known as the Schweizer–Middleditch star, SM star or SM80) as a hot subdwarf sdOB star, and estimated its effective temperature $T_{\mathrm{eff}}$=38,500±4500K, and surface gravity log g=6.7±0.6. From an estimate of the absolute magnitude, $M_v$=6.2±1.8, Schweizer & Middleditch (1980) derived a distance to their subdwarf of 1.1 (+1.4, −0.6) kpc. Since chance projection seemed unlikely, and the distance estimate was in rough agreement with the then exisiting estimates of the distance to the SNR itself, Schweizer & Middleditch (1980) suggested that their subdwarf may in fact be the remnant star, or at least associated with it.

Savedoff & Van Horn (1982) later showed conclusively that the SM star could not be the remnant of the supernova itself, since the time to cool to the observed effective temperature was simply too long, $\sim 10^6$ years compared to the SNR age of $10^3$ years. However, this does not rule out the SM star as a stellar remnant of the *donor* star in a pre-SNIa interacting binary system.

Subsequent far ultra-violet (far-UV) observations with IUE and HST/FOS revealed the presence of strong Fe II and Si II, III and IV lines superimposed on the continuum of the SM star (Wu et al. 1983, Fesen et al. 1988, Wu et al. 1993). The iron lines have symmetrical velocity profiles, broadened up to ∼8000 km $s^{-1}$ FWHM. The Si features are asymmetric, redshifted and centred at a radial velocity of ∼5000 km $s^{-1}$. These features have been used to estimate the mass of iron in the remnant and to map the positions of various shock regions (e.g. Wu et al. 1997, Hamilton et al. 1997). Importantly, though, the presence of redshifted lines in the supernova ejecta suggests that the SM star must lie *behind* the SNR, since they are assumed to originate in material moving away from us on the far side of the remnant.

Measurements of the widths of these aborption lines, coupled with the angular size of the remnant, led Wu et al. (1993) to derive a *lower limit* to the SNR distance of 1.9 kpc. This contrasts strongly with the estimate of Willingale et al. (1995) of 0.7±0.1 kpc, derived from modelling X-ray emission detected in ROSAT PSPC observations. Therefore, we were motivated to re-observe and re-analyse the SM star in order to place tighter constraints on its distance, and hence on the distance to the SNR itself. Secondly, we learnt of the study by Wellstein et al. (1999) which suggests that the prior donor star in an SN Ia progenitor system (an interacting binary) may appear subsequently as a *low mass* hot subdwarf star. This new theoretical result re-opens the question first posed by Schweizer & Middleditch (1980) in the conclusion to their discovery paper: "Can one component of a binary system that forms a Type Ia supernova end up being a

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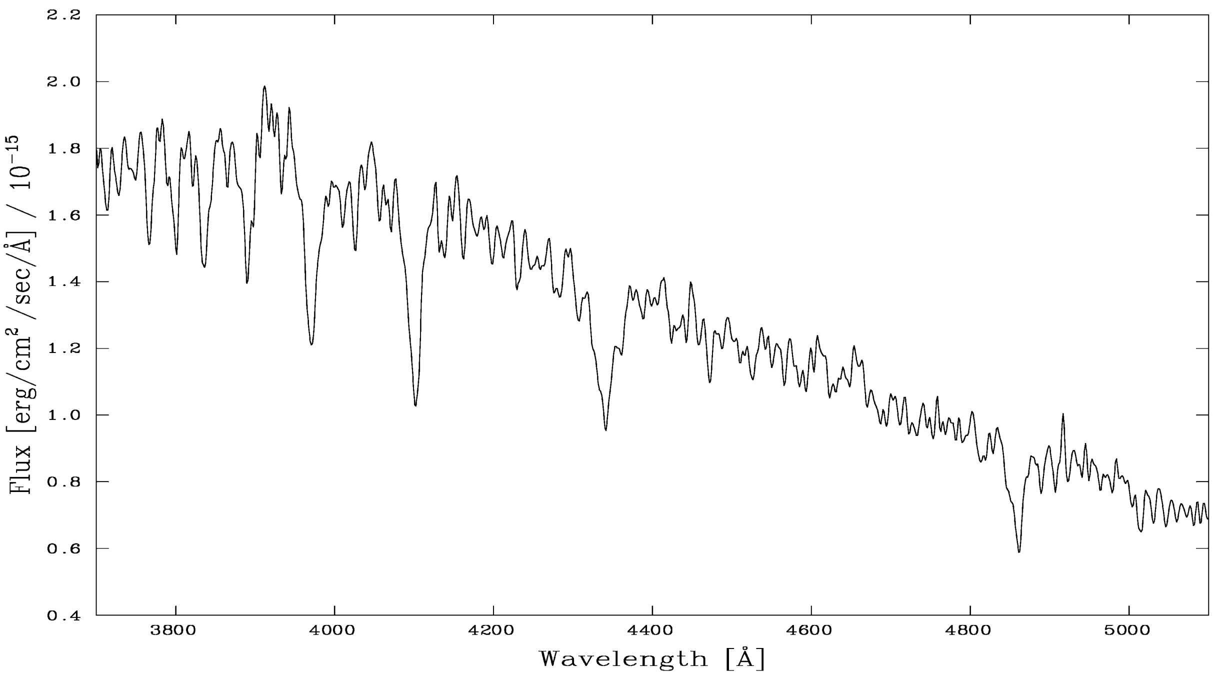


**Fig. 1.** Optical spectrum of the SM star, smoothed with a 3 pixel Gaussian.

hot subdwarf or white dwarf?". In the light of Wellstein et al.'s recent work, we re-address this question.

## 2. Spectroscopy

The SM star was observed for a total of 4000 seconds on 1996 April 14 with the South African Astronomical Observatory's 1.9-m Ratcliffe Telescope, the Unit spectrograph and the Reticon photon counting system (RPCS). The RPCS had two arrays, one which accumulates energy from the source, while the other records sky background through an adjacent aperture. The target was observed for 2000 seconds through one aperture, then for a further 2000 seconds through the second aperture, in order to average out variations between the two light paths. The grating (number 6) was blazed to cover a wavelength range of $\sim$3700Å$-$5200Å with a resolution of $\approx$4Å. Flat fields were obtained at the start and end of the night, and wavelength calibration was provided by a CuAr lamp, which was observed before and after the target. A blue spectro-photometric standard (LTT 6248) was also observed. The reduced, calibrated spectrum is shown in Fig. 1.

## 3. High speed photometry

Recently, multi-periodic pulsations have been discovered in a number of subdwarf sdB stars (the EC14026 stars, Kilkenny et al., 1997). Both radial and non-radial modes are present, although the cause of these pulsations is not fully understood. Theoretical studies have shown that these oscillations may be excited by an opacity bump due to heavy element ionization, giving rise to a metal-enrichment in this driving region (Charpinet et al., 1996). However, why pulsations are observed in some sdBs and not in others remains a mystery.

We observed the SM Star on 1999 September 4th with the South African Astronomical Observatory's 0.75m telescope, together with the University of Cape Town's CCD photometer in high speed mode, in order to search for pulsations. A $\approx$2600 second light curve was obtained, consisting of 20 second exposures separated by essentially zero seconds of dead time. Four comparison stars were also observed at the same time. The differential light curve is shown in Fig. 2. The SM star (star #8 in Fig. 2) shows no evidence of pulsations; the fluctuations in Fig. 2 are merely random noise. The amplitude spectrum (Fig. 3), which has been calculated out to the Nyquist frequency, also shows no evidence for pulsations. However, at V$\approx$16.7 we are clearly unable to detect fluctuations below $\approx$0.05 mags. with this telescope. Many of the known sdB pulsators vary at the level of 0.001$-$0.05 mags., and so clearly we cannot rule out low level pulsations in this object. We suggest that it should be re-observed on a larger telescope.

## 4. Analysis

### *4.1. Spectral analysis*

The H Balmer series is visible in the calibrated optical spectrum (Fig. 1) to H11. HeI is detected at 4026Å, 4144Å, 4472Å and marginally at 4922Å. There is also a marginal detection of HeII at 4686Å.

A grid of synthetic spectra derived from H & He line blanketed NLTE model atmospheres (Napiwotzki 1997) was matched to the data to simultaneously determine the effective temperature, surface gravity and He abundance (see Heber et al. 1999). We find $T_{\rm eff}$=32,900K, log g=6.18 and log (N(He)/N(H))=$-$1.7. While formal statistical errors from the fitting procedure are relatively small (1$\sigma$: $\Delta$($T_{\rm eff}$=)=340K,

**Table 1.** Distance estimates to the SN1006 SNR from the literature

| Author | Year | Distance (kpc) | Method |
|---|---|---|---|
| Minkowski | 1966 | 1.3 | Historical record of brightness |
| Stephenson et al. | 1977 | 1.0±0.3 | Historical record of brightness |
| Winkler | 1977 | 0.9−1.3 | Reverse shock model of x-ray emission |
| Hamilton et al. | 1986 | 1.7 | Reverse shock model |
| Kirshner et al. | 1987 | 1.4−2.1 | Shock velocity & proper motions |
| Hamilton & Fesen | 1988 | 1.5−2.0 | Spherically symmetric hydrodynamic simulations |
| Fesen et al. | 1988 | 1.5−2.3 | Fe line widths, age & angular size of remnant |
| Long et al. | 1988 | 1.7−3.1 | Proper motion of optical filaments |
| Wu et al. | 1993 | >1.9 | FeII line widths & angular size of remnant |
| Willingale et al. | 1995 | 0.7±0.1 | Analysis of x-ray emitting material |
| Laming et al. | 1996 | 1.8±0.3 | Modelling non-radiative shocks |

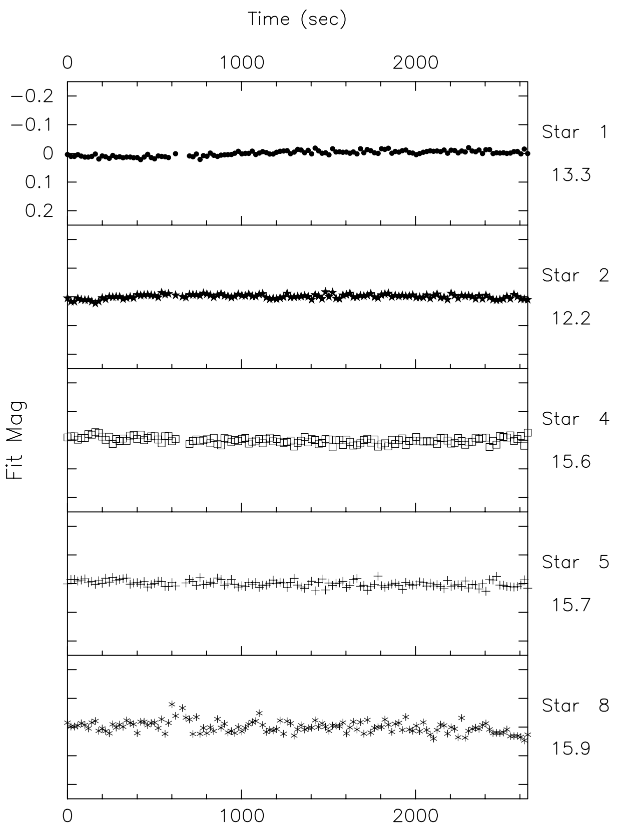


**Fig. 2.** Differential light curve for the SM Star (#8) and four comparison stars in the same field.

$\Delta$(log g)=$\Delta$(log(He/H))=0.1dex), systematics dominate the error budget and are estimated from varying the spectral windows for the profile fitting and the continuum setting to be $\Delta(T_{\rm eff})=\pm1500$K, $\Delta$(log g)=±0.3 dex and $\Delta$(log (N(He)/N(H))=±0.3 dex. These best-fit parameters are unchanged if $H_\epsilon$ is omitted from the fit (since it might be contaminated by CaII). A more precise error estimate would, however, require repeat observations.

Therefore, we find that both the temperature and gravity are at the low end of the large range estimated by Schweizer & Middleditch (1980). With these parameters the SM star resembles an ordinary subdwarf B star close to the zero-age extended horizontal branch (ZAEHB).

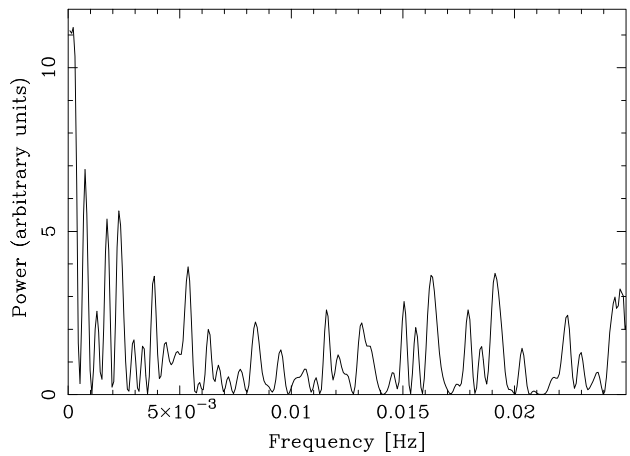


**Fig. 3.** Amplitude spectrum determined from the SM Star's light curve.

### *4.2. Extinction*

Using the Matthews & Sandage (1963) calibration, combined with our model fit parameters, we estimate the colour excess $E_{(B-V)}$=0.16±0.02. From Whitford (1958) we then estimate the visual extinction $A_v=3.0\times E_{(B-V)}=0.48\pm0.06$. Schweizer & Middleditch measured the V magnitude from photoelectric photometry as 16.74±0.02. Therefore, we take the redening corrected magnitude as $V_0=16.26\pm0.07$.

### *4.3. Distance*

Since bolometric corrections for hot subluminous stars are large and somewhat uncertain, we prefer not to make use of them for the distance determination. Instead we calculate the angular radius from the ratio of the observed (dereddened) flux at the effective wavelength of the V filter and the corresponding model flux. Assuming the canonical mass for hot subdwarf stars, $M=0.5\,M_\odot$, we determine the stellar radius from the gravity

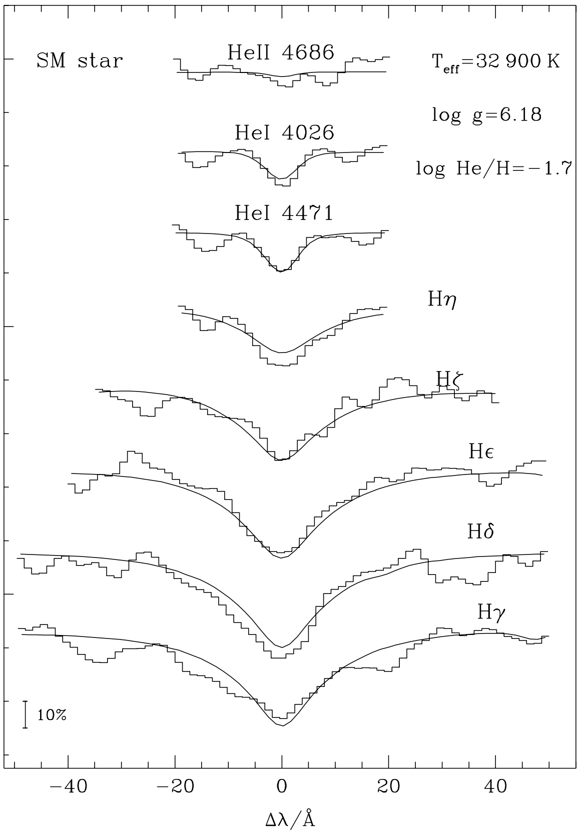


**Fig. 4.** NLTE model fit to the H Balmer lines and He lines detected in the SM Star's optical spectrum.

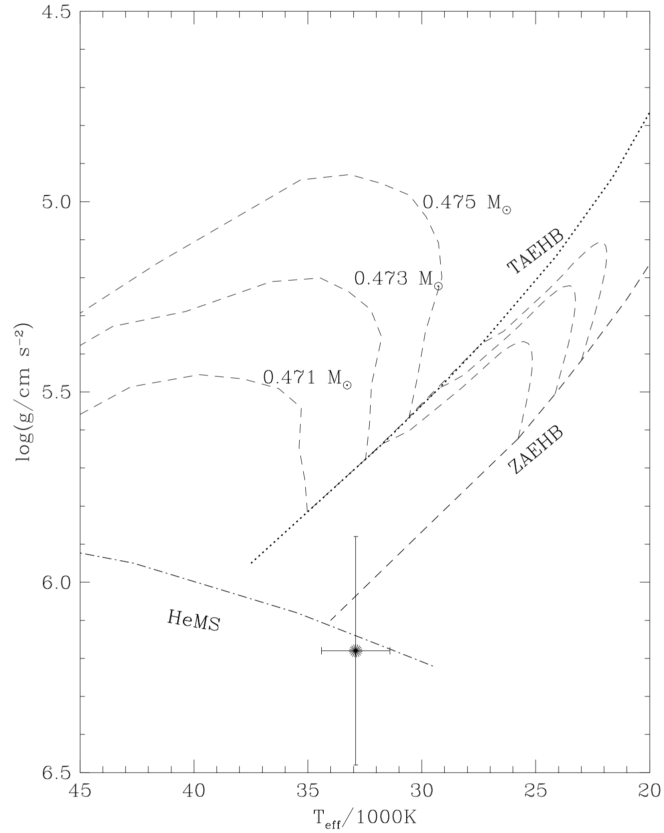


**Fig. 5.** Position of the SM star in the $T_{eff}$/log g plane (large cross). The zero-age extended horizontal branch (ZAEHB) and He main sequence are marked. Loci showing how stars of various masses evolve away from the ZAEHB are also shown.

and finally derive the distance from the angular diameter and the stellar radius. We obtain a distance of d=1485pc which corresponds to an absolute magnitude of $M_V$=5.4. However, the error on log g is large (±0.3 dex), translating to d=1050pc for log g=6.48, or d=2100pc for log g=5.88.

If the SM star has a much lower mass than usually assumed for these objects, as suggested by Wellstein et al. (1999), then the absolute magnitude will be lower and hence the star will be much closer to us. For example, if M=0.2 $M_\odot$ then we find $M_V$=6.4 and d=940pc (assuming log g=6.18). If M=0.1 $M_\odot$, then $M_V$=7.2 and d=650pc.

## 5. Discussion

A new analysis of the Schweizer-Middleditch star, a hot subdwarf which lies along the same line-of-sight as the centre of the SN1006 SNR, has allowed us to place tighter constraints on its atmospheric parameters, and re-assess its distance. Since Wellstein et al. (1999) have demonstrated that the remnant of the donor star in a pre-SNIa binary system could appear as a hot subdwarf, albeit with an abnormally low mass, we can now re-address Schweizer & Middleditch's original question: is the SM star the stellar remnant of one component of the SNIa progenitor binary?

In order to begin answering this question, we need to convince ourselves that the SM star lies at the same distance as the SN1006 SNR. Unfortunately, there is a large range in the SNR distance estimates quoted in the literature. In Table 1, we list the various distance estimates to the SN1006 SNR itself and the method used to obtain that distance. Early estimates, based for example on the historical record of its brightness (e.g. Minkowski 1966) and early models of the X-ray emission, gave distances ∼1kpc. Most of the more recent estimates, based on a variety of theoretical models or measurements of e.g. the expansion velocity or proper motion of optical filaments, place the SNR at a distance of ∼1.5−2.0kpc. The one glaring exception is the estimate of Willingale et al. (1995), 0.7±0.1kpc, based on an analysis of the ROSAT PSPC X-ray image of the SNR.

We find the distance to the SM star 1050<d<2100 pc, assuming that it is an ordinary hot subdwarf. If Willingale et al's distance estimate is correct, then the SM star would lie a long way behind the remnant. In order for it to lie within the remnant, it would have to be of unusually low mass. A mass of 0.1−0.2 $M_\odot$ gives a distance compatible with Willingale et al's estimate, and in that scenario the SM star could indeed then be a remnant of the donor star in an SNIa progenitor system.

However, if Willingale et al's SNR distance estimate is wildly inaccurate, and the more conservative estimates of ∼1.5−2.0kpc are correct (Winkler & Long 1997), then the SM star cannot be a low mass remnant of the donor star in a pre-SNIa binary.

In fact, there are two more compelling arguments against the SM star having any relation to SN1006. Firstly, it is located ≈2.5' south of the projected centre of the remnant, and would have to possess a proper motion of 0.15" per year and a velocity of ≈800km $sec^{-1}$ to have reached its current location. Unfortunately, the star simply does not possess this motion or velocity. Secondly, the presence of red-shifted metal absorption lines superimposed on the SM star's UV spectrum strongly indicate that the star is behind the remnant, since these features almost certainly originate at a shock front on the remnant's far side. Confirmation of this may come from observations of other nearby objects with strong UV fluxes and generally featureless far-UV continuums. Indeed, P.F. Winkler has an HST/STIS program to observe four such objects behind SN1006 during Cycle 8 (two QSOs and two A0 stars, program ID 8244), and one of these objects is even closer to the projected centre of SN1006 than the SM star. These targets are not scheduled to be observed until June-July 2000, but the detection of the same red-shifted features as seen in the SM star (and the non-detection of any additional features with separate velocities) would effectively rule out any exotic origin for these lines, and confirm the location of the SM star behind the SN1006 SNR.

Thus, the SM star can only be the remnant of the donor star in a pre-SNIa binary, such as might have produced SN1006, if the following four criteria are fulfilled: (1) The star has an unusually low mass for a hot subdwarf ($\approx 0.1\,M_{\odot}$), (2) the low distance estimate to the SN1006 SNR of Willingale et al. (1995) is correct, (3) the red-shifted metal lines seen in the SM star's far-UV spectrum originate somewhere other than on the far side of the SNR, and (4) the SM star has a high proper motion and transverse velocity. Unfortunately, at the time of writing, none of these conditions can convincingly shown to be true. However, the tighter constraint we have been able to place on the distance to the SM star in this analysis can now be used to place an upper limit on the distance to the SN1006 SNR itself, and hence constrain the models and methods used to estimate the distances of supernova remnants.

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