The Progenitor of SN1993J Revisited

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ABSTRACT

From HST images with 0.1″ resolution we identify four stars brighter than V=25 within 1.5 arcseconds of SN 1993J that may have contaminated the ground-based flux estimates of the supernova progenitor. Correcting for the contamination, we find that the energy distribution of the progenitor is well matched by a K0 supergiant with $M_V = -7.1$ and an initial mass of $16M_\odot$. The flux of the nearby stars is sufficient to account for the excess blue light seen in pre-explosion observations and there is no evidence that the precursor to 1993J had a blue companion. However, the 1993J progenitor could have had up to a $30M_\odot$ dwarf companion without it being detected in the archival images. Explosion models and observations show that the 1993J precursor had a helium rich envelope. To test whether the helium abundance could influence the energy distribution of the progenitor, we calculated model supergiant atmospheres. The models show that the pre-supernova colors are not strongly affected by the helium abundance longward of 4000Å, and abundances ranging between Solar and 90% helium are all consistent with the observations.

Subject headings: supernovae: general—supernovae: individual (SN 1993J)—stars: evolution

1. Introduction

Our knowledge of the types of stars that become supernovae is based primarily on models of stellar evolution and observations of the environments where supernovae occur. Direct evidence has been scarce. Only two pre-supernova stars have been observed before their explosions, SN1987A (Walborn *et al.* 1987) and SN1993J (Aldering, Humphreys and Richmond 1994 (and references therein); Cohn, Darling and Porter 1995). Preoutburst observations of SN1961V (Filippenko *et al.* 1995) and 1987K (Ryder *et al.* 1993) also exist, but the highly unusual properities of these events suggest that they may be eruptions of extremely massive stars similar to η Carinae. Here, we use Hubble Space Telescope (HST) observations of SN 1993J to help resolve some questions that were raised by the ground-based data on the pre-supernova star.

SN1993J was also an unusual event. It was first classified as a Type II supernova because its spectra showed hydrogen lines (Filippenko 1993; Garnavich and Ann 1993), but soon developed the characteristics of a Type Ib (Filippenko, Matheson and Ho 1993). Several of groups (see the review by Wheeler and Filippenko 1994) concluded that 1993J was a massive star of between $10M_{\odot}$ and $20M_{\odot}$, that had lost most of its hydrogen envelope before exploding. These schemes employ a close companion star to strip the progenitor of its envelope since mass loss through a wind is not efficient at these initial masses. The companion gains mass and may reach more than $15M_{\odot}$ before the supernova explosion (Woosley *et al.* 1994). Höflich *et al.* (1993) point out that the observations can also be reproduced by the explosion of a single star that began on the main sequence at $\sim 30M_{\odot}$ and lost its envelope through a wind.

The properties of the progenitor of SN1993J were estimated by Aldering, Humphreys and Richmond (1994, hereafter AHR) based on an extensive photographic and CCD archive of M81. Their analysis was complicated by the variation in quality of the observations and the crowded field near the supernova. AHR concluded that the progenitor was a K0 supergiant with contamination from one or more blue stars projected near the supernova, possibly light

from the OB association that spawned 1993J.

From a set of CCD images taken in the 1980's to search for novae in M81, Cohen, Darling and Porter (1995) determined that the 1993J progenitor was not a variable at the level of 20%. They also confirmed the Aldering *et al.* estimate of the progenitor color.

Crotts (1995) obtained high quality CCD images well after maximum and found a very red star within 1″ of SN1993J. This star made the AHR images appear elliptical under good seeing conditions and will plague ground-based observers as the supernova fades.

In the course of the Supernova Intensive Study (SINS) collaboration, we have obtained multiwavelength HST images of SN1993J and the nearby field while the supernova was fading. We use these data to estimate the precursor contamination from unresolved stars on ground-based images and attempt to determine the source of the excess blue light seen by AHR. In §2 we describe the observations and photometric reduction. The implications of the HST data to the pre-supernova observations are discussed in §3 and conclusions presented in §4.

2. Observations and Data Reduction

Images of SN1993J were taken on two occasions with the WFPC2 aboard the HST. Short exposures were obtained on 1994 April 18 in filters F366W, F439W, F555W, F675W and F814W, which approximate standard UBVRI bandpasses. After the supernova faded further, images were taken on 1995 Jan 31 in the same filters plus the UV filter F255W.

Aperture photometry was performed on the images using the DAOPHOT packages in IRAF. The aperture was 4 pixels in radius (0.2″) and an aperture correction was applied based on the point-spread function measured from bright stars in the images. The measured counts were converted to standard magnitudes using the transformation algorithm and coefficients given by Holtzman *et al.* (1995).

There are approximately 15 stellar sources within 1.5″ of the supernova that can be identified on the sum of all images obtained in January 1995 (see Figure 1). Of these, only 6 have a B magnitude brighter than 25 and for identification their angular distance and position angle from 1993J have been listed in Table 1.

A distance to M81 of 3.6Mpc has been determined from HST observations of Cepheid variables (Freedman *et al.* 1994). The reddening to 1993J is not as certain. Richmond *et al.* (1994) estimate an E($B-V$) between 0.08 and 0.32 . We use the visual extinction of $A_V = 0.5$ adopted by AHR which is near the middle of the color excess range quoted by Richmond *et al.*. Therefore, a star with an apparent B magnitude of 25 would have an absolute brightness of $M_B \sim -3.5$.

The supernova was still bright in January 1995 ($V \sim 18.9$) and faint stars closer than $\sim 0.25''$ (about 4pc at the distance of M81) would not be resolved if present. Stars with $B >25$ are more than 20 times fainter than the estimated brightness of the progenitor and could not affect the progenitor photometry substantially.

The photometry was repeated on the shorter exposure images obtained in April 1994, and the magnitude differences between the epochs fall within the estimated photometric errors. The final magnitudes in the UBVRI system are the average of the two epochs and are shown in Table 1. The magnitude estimates of SN 1993J are given in Table 2 for the two epochs of HST observations.

The position of the red star reported by Crotts (1995) ($\delta\theta = 0.84''$, P.A. of 344°) is consistent with star A on the HST image. However, their I band brightness of 22.7 is nearly two magnitudes fainter than our HST measurement of 20.87. Also, the HST $R - I = 0.99$ color is much more red than the 0.5 mag reported by Crotts. Our measurements show no significant change in brightness for this star between the two HST observations, implying that it is not variable. The magnitude estimate by Crotts may demonstrate the difficulty in obtaining accurate photometry of closely blended star images even from the best ground-based sites.

3. Discussion

Analysis of the archival images by AHR showed that no single star could fit the progenitor's energy distribution. They suggested that the spectrum is best fit by a slightly reddened K0 supergiant plus light from an OB association surrounding the supernova. From the HST images, we find six stars that fall within the resolution element of typical ground-based observations which may have influenced flux measurements of the progenitor. Star A is red and contributed up to one quarter of the I band flux measured by AHR for the progenitor. Two stars are near the limit if the detection threshold and are too faint to substantially affect the progenitor photometry. The three other stars are blue and may be the source of the excess flux at short wavelengths. The spectral energy distributions for stars A-D are compared with that observed for the progenitor in Fig. 2. Comparing these distributions to the Vilnius spectra (Bessel 1990), star A is well fit by a K5 I star and B to a A2 I star. The spectra of stars C and D are similar to a B0 distribution, but given the distance and estimated extinction (from §2), the stars have $M_V \sim -4.4$ so are smaller than supergiants which have $M_V < -5$.

SN 1993J does not appear to be a member of a cluster or association based on a visual inspection of the HST images. Using the DAOFIND algorithm, a detailed comparison between the density of stars within $2''$ of the supernova with the overall star density on the 'B' frames confirms that there is no statistically significant stellar clustering around the supernova. The diffuse background declines from NW to SE across the field because of the increasing radial distance from the center of M81.

The archival images used by AHR were taken under a wide range of conditions. After subtracting a point-spread-function (PSF) at the position of the supernova, the best images used by AHR left a residual at the position angle of star A. This implied that some of the contaminating light from the nearby stars was eliminated from the SN magnitude estimate under good conditions. However, AHR used a mixture of PSF fitting and aperture photometry (poor seeing) and the latter must have been strongly contaminated with light from stars A-D.

The true energy distribution of the 1993J progenitor must fall between the the limits of the uncorrected AHR results and the distribution with the total flux of stars A-D subtracted. These limits are shown in Fig. 3. In the ultraviolet (UV), the total flux from the surrounding stars is one sigma from the AHR U band flux. Thus, within the errors the blue stars near the supernova could account for all the UV flux of the pre-supernova seen by AHR. The corrected U flux is therefore essentially undetermined.

We also consider a more realistic intermediate case in which the contaminating star contribution declines with distance from the progenitor. Because the ground-based point-spread function is similar to a Gaussian, the degree of contamination is likely to decline as distance in a similar manner. So, to weight the contribution from stars A-D we use a Gaussian distribution,

$$F_\lambda \; = \; \sum_{i=\mathrm{A...D}} F_{\lambda i} \; e^{-r_i^2/2\sigma^2},$$

with a sigma of $1''$. The corrected progenitor energy distribution is shown as a dashed line in Fig.3.

To compare with the revised energy distribution of the progenitor, we have constructed model atmospheres of K0 supergiants using the ATLAS12 code (Kurucz 1993). Because SN 1993J showed evidence of having lost most of its hydrogen envelope (Filippenko, Matheson and Ho, 1993) and evidence that the progenitor atmosphere was helium-rich (Garnavich and Ann, 1994), we have calculated the broad band colors for three helium abundances, Solar, 75% helium and 90% helium. As expected, the colors for the Solar abundance model are very close to those given by Bessel (1990) for the Vilnius spectra. Unfortunately, the three models differ primarily in the UV where the corrected energy distribution of the progenitor is undetermined. At longer wavelengths the K0 I colors of all three models are in excellent agreement with the revised energy distribution of the progenitor.

After accounting for the contamination from nearby stars resolved by HST, we can place a limit on the brightness of any blue companion to the 1993J progenitor. The models show

that the K0 I progenitor had a U magnitude of ~ 24, thus contributed very little to the flux measured by AHR in that band. A hypothetical progenitor companion with $U < 22.4$, added to the light from stars A-D would cause the total UV flux to exceed the AHR measurement of the progenitor by 1 sigma. Conservatively, any progenitor companion could not have been brighter than $U = 22.0$ and still be consistent with the measurements. The AHR uncertainty in the B band is small, so adding an additional star of $B < 23.0$ to the ones accounted for here would exceed the observed flux by 2σ for a K0 I progenitor. So the progenitor companion must have been fainter than an absolute B magnitude of -5.5 assuming a visual extinction of 0.5 mag. Since O6V and later dwarfs have $M_V > -5$ (Humphreys and McElroy 1984) and masses of up to $30M_\odot$, we find that any hypothetical companion to the 1993J supernova could have been very massive and remained undetected.

4. Conclusions

We have used HST images of SN1993J after outburst to search for stars within a ground based resolution element which may have contaminated the archival observations of the supernova precursor. We find four stars within $1.5''$ of the precursor which were, at least partially, included in the progenitor energy distribution determined by AHR. Correcting for this contamination we find:

1) The blue excess seen by AHR can be fully accounted for by the nearby stars. The progenitor was not a member of a significant OB association. Any companion to the progenitor must have had an $M_B > -5.5$ for reasonable assumptions of the reddening and distance to the supernova. The mass of the companion is not strongly constrained, but must be less than $30M_\odot$. This is consistent with the binary mass transfer scenario even for conservative mass exchange.

2) The progenitor was a K0 supergiant with an apparent magnitude of $V = 21.05$. This implies an absolute magnitude of $M_V = -7.15$ for an $A_V = 0.5$. The estimated initial mass of the progenitor is $16M_\odot$ (Schaller *et al.* 1992).

3) Model atmospheres with a wide range of helium abundances fit the observed progenitor energy distribution redward of 4000Å. Although, at shorter wavelengths the models show a greater spread in color with helium fraction, the data is insufficient to differentiate between them.

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Table 1. Stars Within 1.5″ of SN1993J

Star	Offset ″	P.A.[a] °	U (F366W)	B (F439W)	V (F555W)	R (F675W)	I (F814W)
A	0.73	348	...	24.3±0.4	22.85±0.07	21.86±0.05	20.87±0.03
B	1.42	184	23.1±0.4	22.92±0.13	22.90±0.08	23.10±0.07	22.91±0.10
C	1.20	353	23.1±0.3	23.70±0.25	23.80±0.11	23.80±0.15	23.5±0.2
D	1.71	120	22.63±0.25	23.65±0.25	24.0±0.2	24.0±0.2	24.1±0.3
E	0.32	335	...	24.7±0.8	...	...	...
F	0.29	282	...	24.7±0.8	...	...	...

[a] Position Angle, degrees from north through east

Table 2. HST Photometry of SN1993J

Date (UT)	UV[a] (F255W)	U (F366W)	B (F439W)	V (F555W)	R (F675W)	I (F814W
1994 Apr 18	...	18.10	18.37	17.98	16.95	17.17
1995 Jan 31	17.40	18.62	19.19	18.82	17.99	18.66

[a]Magnitude based on $F_{\lambda 2550}(UV = 0) = 3.631 \times 10^{-9}$ ergs/cm^2/s/Å

Figure Captions

Figure 1 - An image of the region around SN1993J. The circle centered on the supernova has a radius of 1.5″. North is up, east to the left. The image is a sum of the frames taken with the f439w, f555w, f675w and f814w filters.

Figure 2 - The energy distributions of the four bright stars within 1.5″ of 1993J compared to the AHR energy distribution for the supernova progenitor. The dotted line shows the sum of all four stars. The points marked with "x" are brightness estimates of star A by Crotts (1995).

Figure 3 - The progenitor energy distribution corrected for the contamination by nearby stars. The thick solid line again shows the AHR progenitor spectrum based on ground-based observations and the dotted line the straight sum of all four nearby stars. The thin solid line shows the corrected progenitor distribution assuming the nearby stars contributed all their light to the AHR measurements. This represents the lower limit to the true progenitor spectrum. The dashed line shows the corrected progenitor energy distribution assuming the nearby stars contribute a fraction of their light weighted by their distance from the supernova.

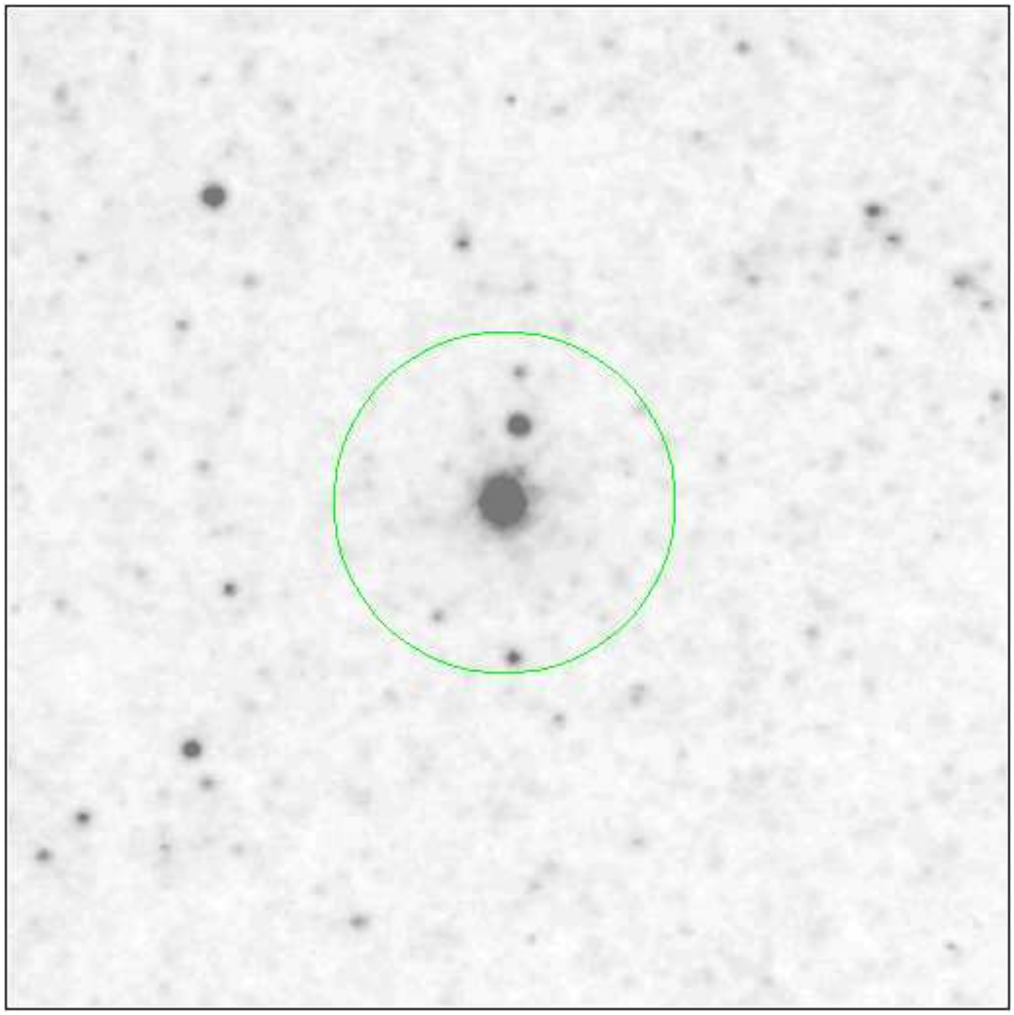

Fig. 1.—

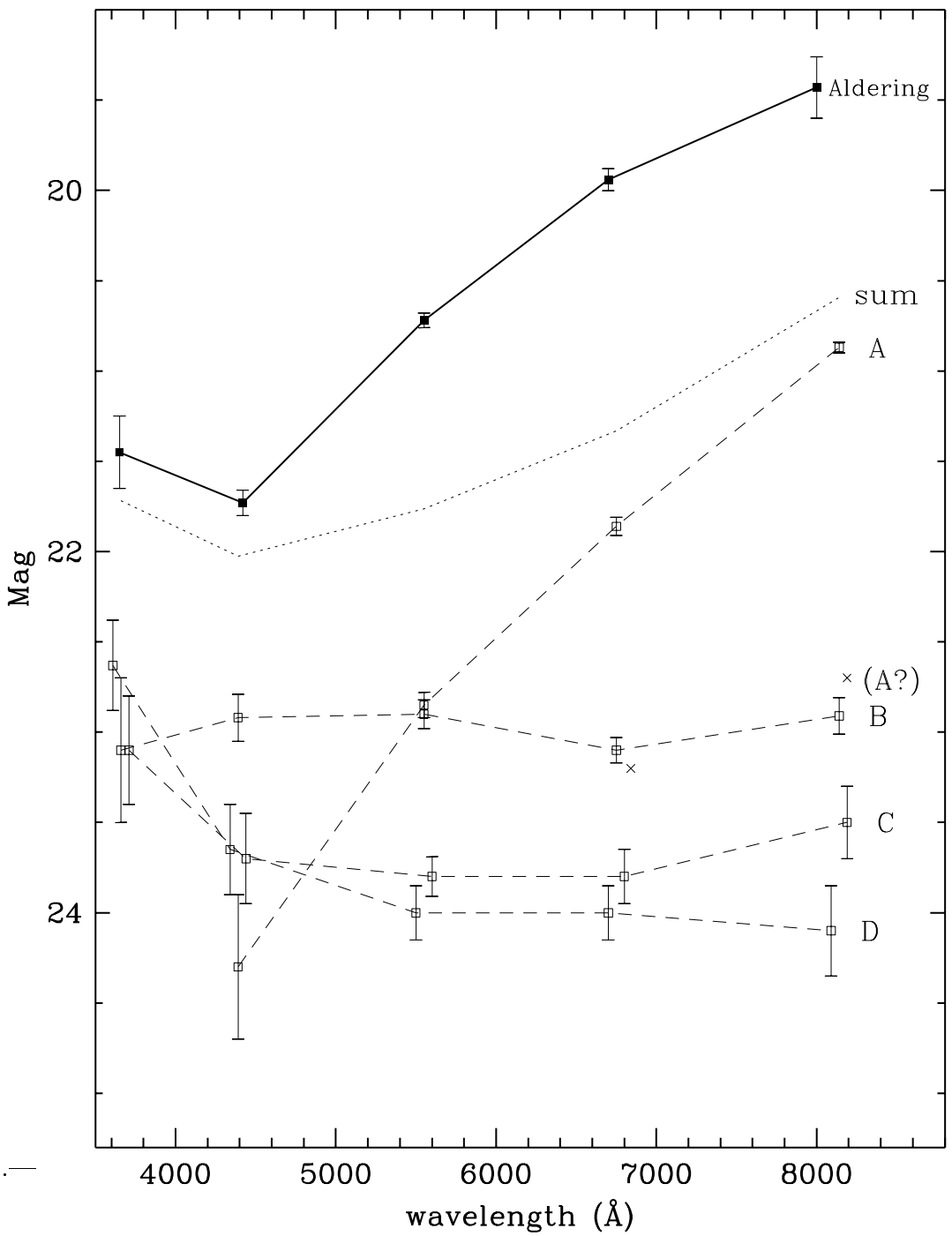
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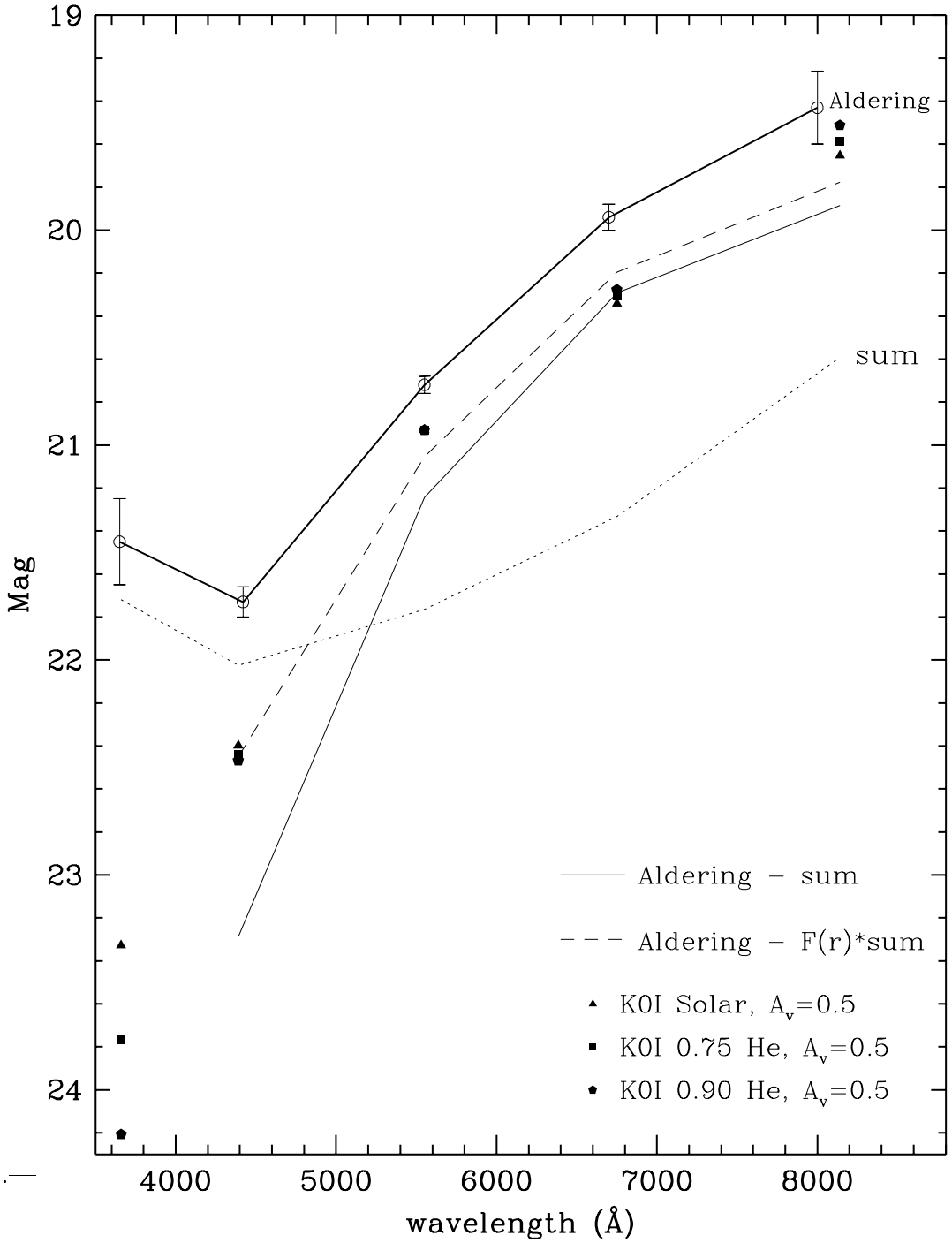
Fig. 2.—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K0I Solar, A_v=0.5
K0I 0.75 He, A_v=0.5
K0I 0.90 He, A_v=0.5

Fig. 3.—