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PRECISE POSITIONS AND OPTICAL SEARCH FOR THE 38 SECOND X-RAY PULSAR NEAR OAO 1653−40 AND UPPER LIMIT ON X-RAY EMISSION FROM V861 SCORPII

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ABSTRACT

The region of the binary system V861 Scorpii, whose secondary has been suggested as a black hole candidate, was observed with the *HEAO 1* X-ray observatory during an 8 hour pointed observation on 1978 September 4. An upper limit of 1.0 μJy (3 σ) is placed on X-ray emission from V861 Sco during this observation. This effectively removes the secondary from the list of black hole candidates. We confirm the presence of a 38 s pulsar in the region, give precise (0.63 arcmin^2) positions, and describe a search for the optical counterpart.

Subject headings: pulsars — X-rays: sources

I. INTRODUCTION

V861 Scorpii (=HD 152667) is a 7.848 day spectroscopic binary system with a B0 Vae primary and an unseen secondary no more luminous than a B3 V star (Walker 1971, 1972). It has been proposed as the optical counterpart of the X-ray source OAO 1653−40, discovered with the *Copernicus* satellite in 1978 April and May, on the basis of two declines in X-ray intensity approximately four 7.8 day periods apart (Polidan *et al.* 1978). The *Copernicus* observation of an ultraviolet flare from V861 Sco within ~1 hour of an X-ray turn-on on 1978 September 3.3 (Polidan *et al.* 1979) supported the identification. The mass function (0.487 $M_\odot$; Walker 1971) and probable $>20\ M_\odot$ mass of the primary (Hutchings 1979) indicate a mass of $>7\ M_\odot$ for the secondary, larger than the theoretical limit for a neutron star; thus the discovery of X-rays from the region led to the suggestion that the secondary is a compact object, and hence a black hole (Polidan *et al.* 1978).

A pointed observation of the region was carried out with the *HEAO 1* X-ray observatory between 0^h and 8^h (UT) on 1978 September 4 (concurrent with part of the 1978 September 2.9–5.5 *Copernicus* observation), leading to the discovery by the *HEAO 1* A-2 group at Goddard Space Flight Center (GSFC) of a 38.22 s modulation in the X-ray flux of a source in the region of V861 Sco (White and Pravdo 1979). The same *HEAO 1* observation provided high-energy (13–180 keV) X-ray data (MIT/UCSD A-4 experiment; Byrne *et al.* 1979), and high angular resolution results from the modulation collimator (MC) experiment which we present here. The MC results confirm the presence of the pulsations, yield precise positions which exclude V861 Sco as the pulsating source, and place a 3 σ upper limit of 1.0 μJy (averaged over 1.5–13.5 keV) on X-ray emission from V861 Sco (1 μJy = 2.4×10^{-12} ergs s^{-1} cm^{-2} keV^{-1}). The A-2 and A-4 results also exclude V861 Sco as the pulsating source.

II. V861 SCORPII

The 8 hour observation yielded 13,900 s of MC1 (30″ FWHM collimator) data and 16,500 s of MC2 (120″ FWHM) data. (For a description of the instrument and analysis procedure see Schwartz *et al.* 1978 and Gursky *et al.* 1978.) The pulse-shape discriminator (PSD) accepted variable numbers of non–X-ray background counts as X-rays due to orbital fluctuations in the non–X-ray background. We corrected the X-ray data for these variations by binning the non–X-ray background counts in the same way as the X-ray data, then compensating the X-ray data for deviations from the average PSD rejection rate (see Dower *et al.* 1980). Our final results are consistent with those obtained without this technique if the data are restricted to times when the non–X-ray background rate was near its minimum value.

The data were binned modulo the collimator periodicities about the position of V861 Sco. The MC2 data, folded modulo the 16′ band spacing, are shown in Figure 1*a*. No significant X-ray emission is detected from V861 Sco. Any signal from V861 Sco would appear at phase 1.0 with a full width at zero intensity of 0.25. Since phases 1.0–1.125 contain counts from one or more other sources in the 4° × 4° (FWHM) field of view, we use data only from phases 0.875–1.0 to determine an upper limit on the flux density from V861 Sco. We find an upper limit (3 σ) of 1.0 μJy (averaged over 1.5–13.5 keV) from the MC2 data for an assumed Crab-like spectrum. A similar analysis of the MC1 data yields a 3 σ upper limit of 2.5 μJy.

The region of V861 Sco was observed during 1978 September 2.9–5.5 with the ultraviolet spectrometer and the 2°.5 × 3°.5 (FWHM) X-ray detector on *Coper-*

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nicus (Polidan *et al.* 1979). Steady X-ray emission from the region was detected during the entire period September 3.3–5.5 (Polidan, private communication) at ~7 *OAO* counts per 62.9 s, slightly less than half the maximum rate of 15 *OAO* counts per 62.9 s observed from this region with *Copernicus* in 1978 April and May. The spectrum for those observations, given in Figure 3 of Polidan *et al.* (1978), yields a flux density at maximum of 23 μJy averaged over 5.3–9.3 keV. Thus, if we assume the same spectrum, we calculate a flux density of 11 μJy for the 1978 September observation. Our 1.0 μJy upper limit therefore shows that V861 Sco was not the source of the September 3.3–5.5 emission and that the ~1 hour coincidence between the ultraviolet flare from V861 Sco and the September 3.3 X-ray turn-on must have been fortuitous. We suggest as well that the source detected with *Copernicus* in 1978 April and May in this crowded region was also not V861 Sco.

If V861 Sco is not an X-ray source, the secondary cannot be considered a black hole candidate. The detection of hard X-rays from the system would indicate that the secondary is a compact object; since no such detection has been convincingly demonstrated, the question of the nature of the secondary is still open. Its probable ~7 $M_{\odot}$ mass and the optical limit on its luminosity (not greater than that of a B3 V star; Walker 1972) indicate that the secondary could be a B V or an A V star.

III. THE 38 SECOND PULSAR

a) *X-Ray Position*

We obtained precise positions for the 38 s pulsar by rebinning our data about the position obtained by the MIT/UCSD *HEAO 1* A-4 group (Byrne *et al.* 1979). We used 6000 s of MC1 data and 8800 s of MC2 data taken when the non–X-ray background counting rate was low. Contributions from three X-ray sources are observed in our data: the pulsar, 4U 1702−42, and an uncataloged third source. Counts due to the pulsar and to the third source overlap in collimator phase in the MC1 data (Fig. 1*b*). The pulsar is similarly confused with 4U 1702−42 in the MC2 data (Fig. 1*c*). The fact that the pulsar is confused with different sources

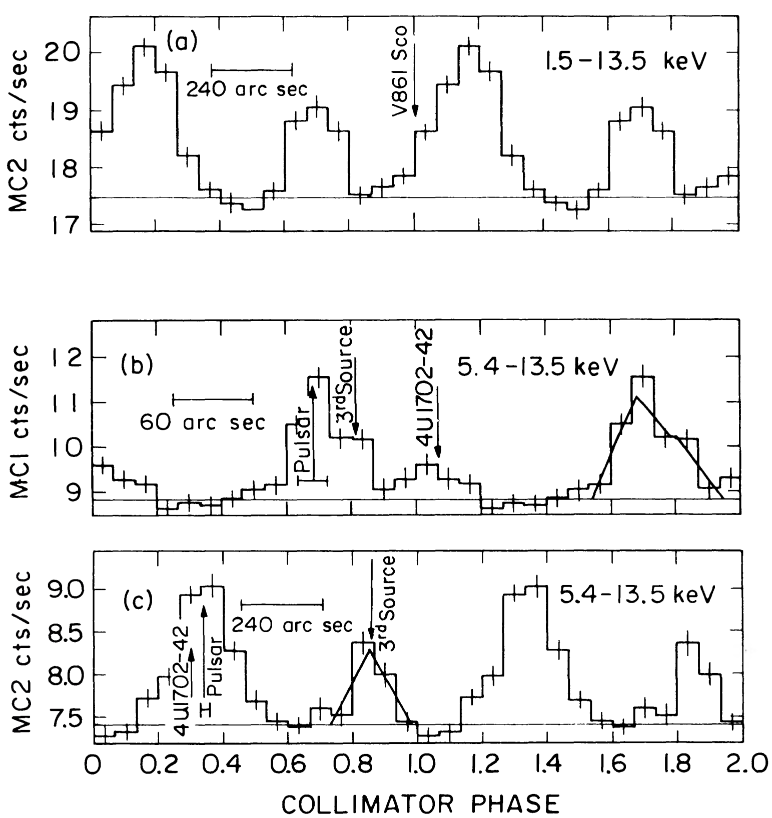

FIG. 1.—Counting rate as a function of collimator phase. Vertical bars are 1 σ errors. Arrows show the centers of the triangular collimator responses to the indicated sources. The horizontal lines are the adopted background rates. (*a*) MC2 data binned about the position of V861 Sco. Any signal from V861 Sco would appear at phase 1.0 ± 0.125 (full width zero intensity). One count s^{-1} corresponds to 1.5 μJy. We place a 3 σ upper limit of 1.0 μJy (1.5–13.5 keV) on X-ray emission from V861 Sco. (*b*) MC1 data, from a narrow range of satellite orientation (see text), binned about the center of the A-4 error box (Byrne *et al.* 1979). The short horizontal bar at phase 0.67 is the 90% confidence error in the location of the pulsar after allowing for source confusion and aspect uncertainties. The profile at phase ~1.7 shows the collimator response to the best-fitting two-point-source model. (*c*) MC2 data binned about the center of the A-4 error box. The triangle centered on the third source shows the collimator response to a point source.

in data from the two collimators enabled us to deduce that 4U 1702−42 and the third source are respectively ~30% and ~55% as strong as the pulsar in our high-energy channel (5.4–13.5 keV). Since the pulsar is the hardest source in our data (energy spectral index 0.4; White and Pravdo 1979), only high-energy channel data were used to obtain positions for the pulsar.

We confirmed the identity of the hardest source as the pulsar by first searching all collimator phase bins for evidence of a 38.22 s modulation. Only bins containing this source show such modulation. We then tested these data for modulation with 40 periods in the range 38.00 s to 38.40 s by performing a χ^2 test of the hypothesis that the source is constant. Significant modulation is seen only with a 38.22 s period: for nine degrees of freedom, we found a χ^2 per degree of freedom of 6.50 for data in the 5.4–13.5 keV range and 1.26 in the 1.5–5.4 keV range, indicating that the modulation is formally present at the >99% confidence level in the high-energy channel but only at the 75% confidence level in the combined low-energy channels. The phase-averaged flux density is ~8 μJy (5.4–13.5 keV), with an uncertainty of ~25% due to source confusion. This is consistent with the results of White and Pravdo (1979), and suggests that most or all of the X-ray emission detected with *Copernicus* in 1978 September was from the pulsar.

We obtained one set of celestial lines of position for the pulsar from 2200 s of MC1 data taken when the satellite was in a narrowly restricted range of orientations about the view axis. This range was chosen to maximize the separation in collimator phase of the three sources. In these data, shown in Fig. 1*b*, the counts due to the pulsar are clearly separated in phase from those due to 4U 1702−42. We fitted a two-point-source model to the counts from the pulsar and the third source to deduce the MC1 lines of position of the pulsar. Three parameters were allowed to vary: the positions of the two sources and the ratio of their strengths. The resulting lines of position for the pulsar are the same as those found by fitting a single-source model to the 6000 s MC1 data set, demonstrating that the deduced position of the pulsar is unaffected by the presence of the third source. The presence of the third source increased the positional uncertainty in MC1 by ~7%, to ±13″ (90% confidence).

We then used the MC2 data to obtain a second set of celestial lines of position for the pulsar. We fitted a two-source model to the data in MC2 collimator phases 0.1–0.6 by the same method used on the MC1 data. The resulting 90% confidence contour in parameter space is consistent with the strength of 4U 1702−42 in the MC1 data and with the *SAS 3* position for 4U 1702−42 (Jernigan *et al.* 1978). This analysis yielded a 90% confidence width for the MC2 lines of position for the pulsar of ±16″.

The intersections of the two sets of lines of position yield multiple error parallelograms. The positions of the centers of some of these parallelograms are indicated by crosses in Figure 2. Only three of these are consistent with both the error box obtained by the A-4 group (Byrne *et al.* 1979) and the error box obtained by the A-2 group (White and Pravdo 1979); one more parallelogram is just outside the 90% confidence A-4 error box (No. 1 in Fig. 2). The coordinates and error regions of these four parallelograms (Nos. 1–4) are listed in Table 1; finding charts are shown in Figure 3 (Plate L21). Coordinates of 10 more parallelograms just outside the A-2 and A-4 boxes are also given in Table 1. Finding charts of these regions are available from the authors.

b) *Optical Search*

Low-resolution spectra were taken with the IPCS and the SIT vidicon on the AAT and CTIO telescopes, respectively, of 25 stars in a search for the optical counterpart. Table 2 lists these stars, approximate magnitudes and spectral types, and an approximate color measured from the slope of the continuum between 4700 Å and 4000 Å. There may be substantial uncertainty in color for the reddest objects. No star examined was a clear candidate. However, two spectra of star 8, taken four nights apart, show heavy reddening ($B - V \approx 2$), and either possible emission around λλ4640–50 and λ4686 or unexplained absorption near λ4760. They also demonstrate variability in the He I lines: the first shows possible absorption only at He I λλ5015 and 5876, while the second, extending only to 5000 Å, shows He I λλ3819, 4026, and 4471 lines in absorption. We classify star 8 as a B star on the basis of the He I features, although the strength of the Balmer absorption lines is greater than that normally found in B type spectra. Another object, star 38 (marked but not visible in Fig. 3), must be extraordinarily red; it was easily

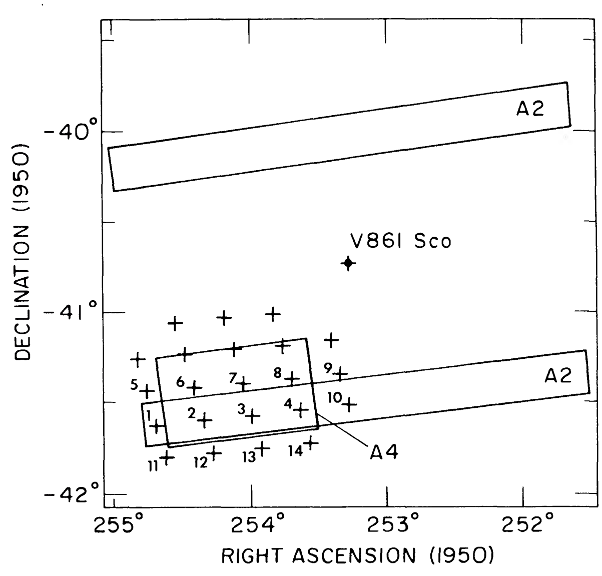

FIG. 2.—The region of the pulsar and V861 Sco, showing the celestial position for V861 Sco and positions for the pulsar: the 95% confidence A-2 (White and Pravdo 1979) and 90% confidence A-4 (Byrne *et al.* 1979) error boxes, and some possible MC positions (*crosses*). The actual MC parallelograms are about half as high (N-S) and 0.1 as wide (E-W) as the crosses.

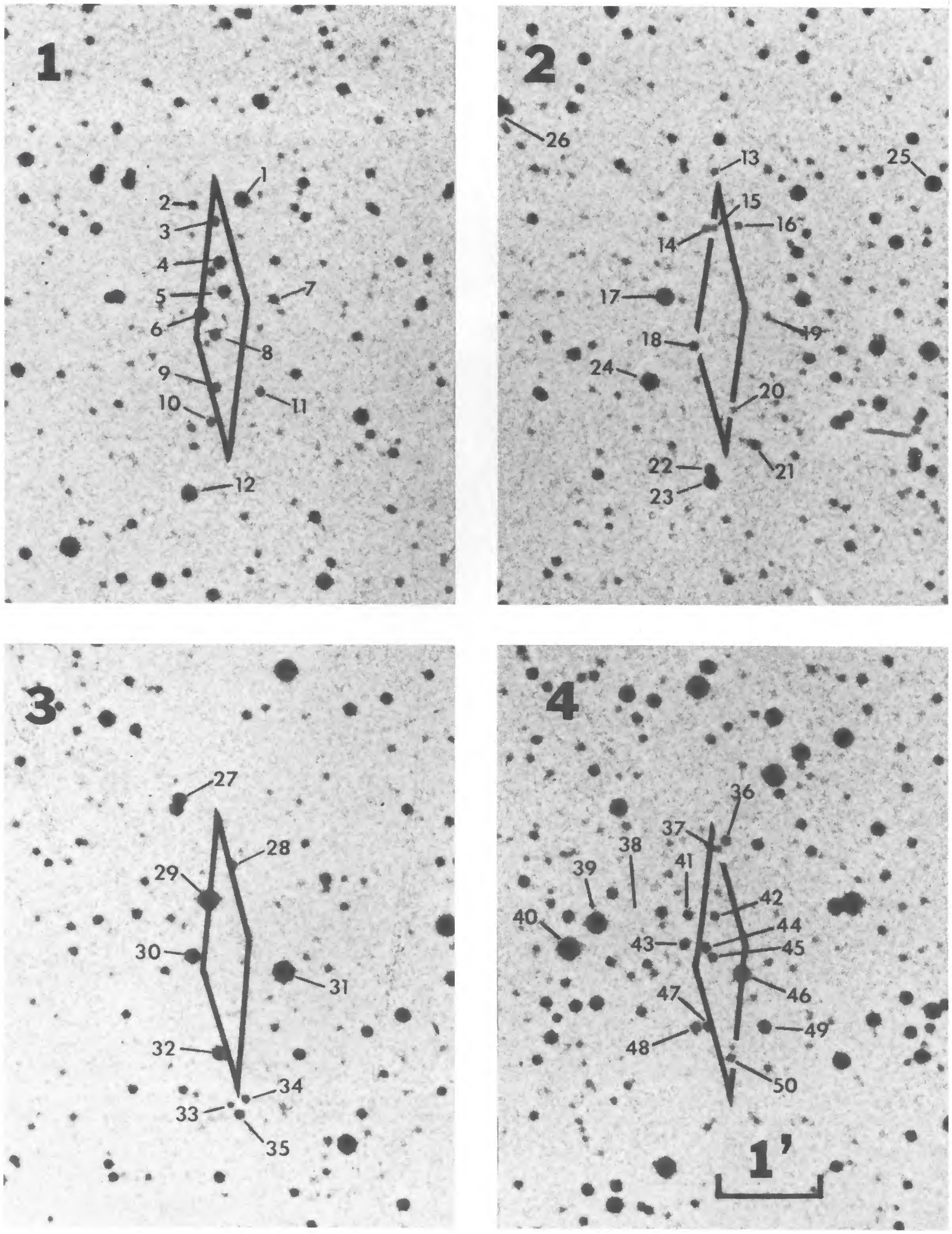

FIG. 3.—The 38 s pulsar finding charts enlarged from an ESO quick blue survey plate, showing the 90% confidence error parallelograms numbered 1–4 in Table 1 and Fig. 2. North is up and east is to the left. Twenty-five stars listed in Table 2 have been investigated spectroscopically. Star 8 shows spectral variability. The position of star 38, a very red object not visible on this plate, is indicated.

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visible on the (red sensitive) television guider at the CTIO 4 m telescope, but a 15 minute exposure in the blue spectral region gave no spectrum. We note that parallelograms 5–14 in Table 1 have not yet been searched, and that the search of parallelograms 1–4 is incomplete.

TABLE 1

HEAO 1 MC ERROR PARALLELOGRAM CENTERS AND 90% CONFIDENCE OFFSETS

PARALLELOGRAM	CENTER R.A. (1950)	CENTER decl. (1950)
1[a]	$16^h58^m40^s.3$	−41°37′17″
2	16 57 16.8	−41 35 59
3	16 55 53.4	−41 34 38
4	16 54 30.0	−41 33 12
5[a,b]	16 58 55.3	−41 26 27
6	16 57 32.0	−41 25 10
7	16 56 8.9	−41 23 50
8	16 54 45.7	−41 22 25
9	16 53 22.6	−41 20 57
10	16 53 6.7	−41 31 44
11[a]	16 58 25.2	−41 48 06
12	16 57 1.5	−41 46 48
13	16 55 37.9	−41 45 25
14	16 54 14.3	−41 44 00

NOTE.—Offsets to 90% confidence error parallelogram corners (″): 13 N, 4 W; 81 S, 5 W; 13 S, 14 E; 81 N, 5 E.

[a] Parallelograms 1, 5, and 9–14 are ∼3′ to ∼11′ outside the *HEAO 1* A-4 90% confidence box (Byrne *et al.* 1979).

[b] Parallelograms 5–14 are ∼1′ to ∼5′ outside the *HEAO 1* A-2 95% confidence box (White and Pravdo 1979). Finding charts for these are available from the present authors (c/o H. V. B.).

c) Discussion

The 38 s pulsar is of particular interest because it is the first X-ray pulsar found with a period between 10 s and 100 s, and thus falls in a gap in the pulse-period distribution (White and Pravdo 1979). There are 10 in the decade between 100 s and 1000 s, and five in the range 0.7 s–10 s (see Bradt, Doxsey, and Jernigan 1979). The shape of this distribution is as yet unexplained; it may be accidental, since the total number of known X-ray pulsars is only 16.

Further X-ray observations of the 38 s pulsar are needed to search for evidence of binary behavior and to provide information on the period derivative. Rappaport and Joss (1977) give an expression for spin-up due to accretion torques:

$$\frac{\dot{P}}{P} \approx -3 \times 10^{-5} f \left(\frac{P}{1\text{ s}}\right)\left(\frac{L}{10^{37}\text{ ergs s}^{-1}}\right)^{6/7} \text{yr}^{-1},$$

where P is the pulse period, $\dot{P}$ its time derivative, L the X-ray luminosity of the pulsar, and f a dimensionless function of order unity. If we apply this expression to the 38 s pulsar and integrate the spectrum given by White and Pravdo (1979) to obtain L/D^2, we expect $\dot{P} \sim -0.03\ (D/10\text{ kpc})^{12/7}$ s yr^{-1}, which should be easily observable. Here, D is the distance to the pulsar; since it is 15° from the galactic center and only 0°.5 above the galactic plane, it could be as much as 25 kpc distant and still be only ∼200 pc above the plane.

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TABLE 2

STARS EXAMINED AT CTIO AND AAT

Star Number	m_B[a] (mag)	Approximate Color[b] (mag)	Type	Star Number	m_B (mag)	Approximate Color (mag)	Type
1	15	1.2	K2 II/III[c]	31	12	0.7	G0
3	18	1.0	A7/F3	32	15	1.1	G0
4	16	0.8	F0/2 V	36	18	0.8	F:
5	16	1.5	early G	38	...	>2	(see text)
6	16	0.8	G8/K0 IV:[d]	39	13	0.3	B8/A0 V
8	17	1.3	B(var)[e]	40	12	1.0	K0/2 II/III[c]
17	14	0.7	G8/K0 III	42	18	1.1	F: :
18	18	0.7	G/K V	43	17	1.0	K0/2 III
24	14	0.6	A2 V	44	17	1.0	G IV:
25	15	1.2	K0 II/III[c]	45	18	1.0	K III:
26	13	0.5	G2/8	46	14	0.7	G0
29	13	0.7	G0	47	17	0.9	K V: :
30	15	0.6	G0				

[a] Estimated from image size on ESO quick blue survey print.

[b] Color = 2.5 log[f_λ (4700)/f_λ (4000)] + 0.34.

[c] Strong CN features.

[d] Colon indicates uncertain spectral type.

[e] Heavily reddened ($B-V \approx 2$).

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