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DISCOVERY OF THE OPTICAL COUNTERPART OF THE TRANSIENT X-RAY BURSTER CENTAURUS X-4[1]

CLAUDE R. CANIZARES[2] AND JEFFREY E. MCCLINTOCK[2]
Department of Physics and Center for Space Research, Massachusetts Institute of Technology
AND
JONATHAN E. GRINDLAY[2,3]
Center for Astrophysics, Harvard College Observatory, and Smithsonian Astrophysical Observatory, Cambridge, Massachusetts
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ABSTRACT

We have discovered the optical counterpart of the X-ray transient observed by Kaluziensky and Holt in 1979 May. This is almost certainly the historical transient Cen X-4 which was first discovered in 1969 and which has been dormant for the past decade. Oda has shown it to be a Type I burster as well. Our observations, carried out at the Cerro Tololo Inter-American Observatory, show that the star brightened to 12.8 mag from $\approx$19 mag, and then faded at an average rate of 0.12 mag per day. The colors are very blue at maximum but they redden as the star fades. There is evidence for erratic variability on time scales of days, minutes, and possibly seconds. The spectrum shows weak Balmer, He II λ4686, and N III λλ4634–42 emission and strong emission complexes at λλ3775–3975. The former are characteristic of many X-ray source counterparts. The latter are particularly prominent in the spectra of the counterparts of X-ray bursters. The X-ray and optical characteristics of Cen X-4 classify it both as a member of the class of soft X-ray transients like A0620−00 and A1524−61 and as a burster. Since there are several reasons to believe that the soft transients are in binary systems, the link to bursters established by Cen X-4 strengthens considerably the hypothesis that X-ray bursters are in binary systems. Our observations support the hypothesis that at least some of the light comes from an accretion disk and that X-ray heating plays an important role in the optical emission.

Subject headings: X-rays: bursts — X-rays: sources

I. INTRODUCTION

We report the discovery and subsequent study of the optical counterpart to an X-ray nova which is almost certainly the historical transient Centaurus X-4 (a preliminary announcement was given by Canizares, McClintock, and Grindlay 1979*a*). Cen X-4 was first detected as an X-ray source with the Vela satellites in 1969 July (Conner, Evans, and Belian 1969; Evans, Belian, and Conner 1970; Belian, Conner, and Evans 1972). It reached a flux more than 35 times that of the Crab nebula and then faded over the next several months to remain dormant for the past decade. The reappearance of Cen X-4 was detected with the All Sky Monitor experiment on the *Ariel 5* satellite by Kaluziensky and Holt (1979*a*, *b*, 1980), who observed that the flux began increasing on 1979 May 11, peaked at 4 times the flux of the Crab on May 17, began declining on May 20, and fell below the threshold of their instrument on June 8.

Following their initial detection of the source, Holt and Kaluziensky telegraphed the Cerro Tololo Inter-American Observatory, where most of our work was carried out, to alert interested observers. They noted that the position of the source was consistent with the more accurate position for Cen X-4 recently obtained by Terrell *et al.* (1979) from a re-analysis of data from the 1969 outburst. Dr. Martha Liller kindly obtained a plate of the region for us with the 4 m telescope at 01:40 UT 1979 May 19. We compared the full ~1 square degree plate against the Palomar Observatory Sky Survey (POSS) print of the region and found one star which had brightened by several magnitudes. The positional agreement with Cen X-4 and the characteristics of the object revealed through the subsequent photoelectric and spectroscopic observations reported below leave no doubt about the identification.

II. OBSERVATIONS

a) Position

In Figure 1 (Plate L9) we show prints of the 4 m plate (baked IIIa-J + GG385, 15 m exposure at prime focus) and the POSS blue plate. The position of the nova is $\alpha = 14^h55^m19^s.63 \delta = -31°28'09''.0$ ($\pm 0''.5$; 1950), This is 0°.24 from the Vela satellite position of Cen X-4 ($14^h54^m.5$, $-31°18'$) which has a quoted uncertainty of 0°.2 (Terrell *et al.* 1979).

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[2] Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is operated by the Association for Research in Astronomy, Inc., under contract with the National Science Foundation.
[3] Alfred P. Sloan Research Fellow.

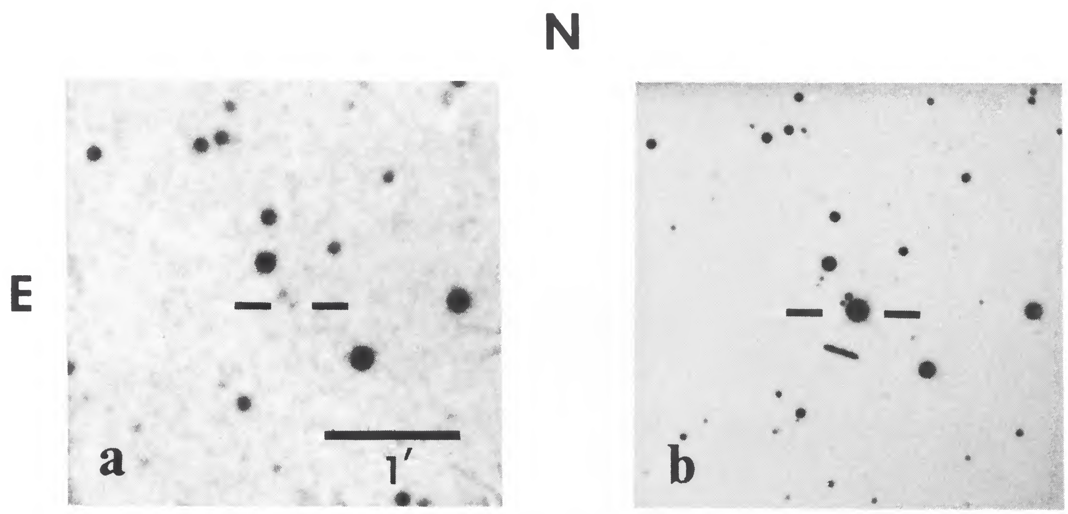

FIG. 1.—The brightening of Cen X-4. (*a*) The Palomar Observatory Sky Survey blue print (© National Geographic Society) showing Cen X-4 in its quiescent state. (*b*) The discovery plate obtained by M. Liller at the prime focus of the CTIO 4 m telescope on 1979 May 19 (baked IIIa-U +GG385, 15 m exposure).

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b) Light Curve

The light curve of Cen X-4 is plotted in Figure 2. The magnitude at discovery was estimated from the 4 m plate. For several nights following discovery, we carried out photoelectric photometry of the object with the CTIO 1.5 m telescope and an RCA C31034A phototube. After our photometry run was over, Dr. Hugh Harris kindly continued to observe the source each available night on the 0.9 m and 0.6 m telescopes. Ronald Remillard performed photoelectric photometry at the McGraw Hill Observatory[1] on June 24. We also include in Figure 2 less accurate values of the magnitude based on our spectrophotometry of Cen X-4 described below. Magnitudes of $\sim$18 and $\sim$18.5, respectively, have been estimated by Seitzer, Smith, and Ross (1979) from a plate obtained on June 14 at Mount Stromlo Observatory and by Wyckoff (1979) from spectrophotometry at the CTIO 4 m on July 15. Figure 1 shows that Cen X-4 is near the POSS plate limit when it is quiescent. We estimate its magnitude at minimum to be $\gtrsim$19 mag.

The data of Figure 2 show a relentless if somewhat erratic decline at an average rate of $\sim$0.12 mag per day from May 19 to June 5. The X-ray "light curve" is qualitatively similar (Kaluziensky and Holt 1980) and shows some but not all of the same erratic features. The rise from May 19 to May 20, and the arrested decline during May 22–23 and May 28–31 appear in both the X-ray and optical data. At maximum, the 1–10 keV X-ray flux is $\sim$40 times the bolometric optical flux, assuming a temperature of $kT = 4$ keV for the X-ray spectrum and a bolometric correction of 2 mag and an extinction $A_v \sim 0.5$ for the optical.

[1] The McGraw Hill Observatory is operated jointly by the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology.

The relationship between the optical and X-ray fluxes from Cen X-4 is shown in the inset of Figure 2, in which we have plotted a linearized optical flux in the V band ($F_{\rm opt}$) against the corresponding 3–6 keV X-ray flux (F_x) from Kaluziensky and Holt (1980). There is a clear correlation between the two fluxes, although there is also considerable scatter. Some of the scatter may be due to the lack of strict simultaneity between the X-ray and optical measurements (see § II*d*). The curve shows the parametrization $F_{\rm opt} = aF_x^{\alpha}$ with $a = 2.4$ and $\alpha = 0.64$. If the optical emission were largely the result of X-ray heating of a companion star or an accretion disk with fixed geometry, then one would expect such a relationship to hold, although in general α is a weak function of the temperature and luminosity of the X-ray source (see Milgrom and Salpeter 1975; Milgrom 1976*a*, *b;* Endal, Devinney, and Sofia 1976). Similar relationships can be found for the optical emission associated with X-ray bursts (Grindlay *et al.* 1978; Hackwell *et al.* 1979) and with the flaring X-ray pulsar 4U 1626−67 (McClintock *et al.* 1980).

The duration of the optical outburst of Cen X-4 is considerably shorter than those associated with the soft X-ray transients A0620−00 (see Whelan *et al.* 1977) and A1524−61 (Murdin *et al.* 1977). The average rate of decline of the magnitude of Cen X-4 is nearly 10 times faster than for the other two novae. The X-ray outburst of Cen X-4 is also considerably shorter and $\sim$8 times less intense than its 1969 outburst (Evans, Belian, and Conner 1970). The latter resembles more closely the X-ray outburst of A0620−00 and A1524−61. Scaling from the present data suggests that it was accompanied by an optical nova of $\sim$11.5 mag. If the shorter-duration outbursts are more typical of Cen X-4, then it is not surprising that Liller (1979) failed to find any record of an earlier brightening

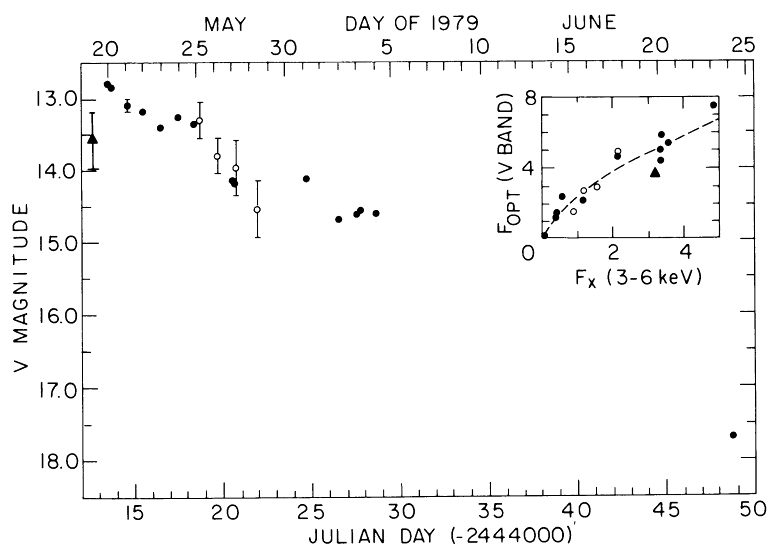

FIG. 2.—The light curve of Cen X-4. The X-ray flux rose on 1979 May 11. The solid triangle is from the discovery plate, the filled circles are from photoelectric photometry, and the open circles are from spectrophotometry. The inset shows the optical flux (linear scale) versus X-ray flux from Kaluziensky and Holt (1980), together with the curve $F_{\rm opt} = aF_x^{\alpha}$, with $a = 0.24$ and $\alpha = 0.64$.

of the source in the historical plates of the Harvard collection, which have limiting magnitudes of 13.5–16 mag.

c) Colors

The $(B-V, U-B)$ colors of Cen X-4 were $(0.05 \pm 0.03, -0.87 \pm 0.05)$ on May 20 and $(0.10 \pm 0.03, -0.87 \pm 0.05)$ on May 23 and 24. These are very similar to the colors of the transient A0620−00 (van den Bergh 1976) and of HZ Her at its maximum (Boynton *et al.* 1973). By June 24 the colors of the star had become $(1.07 \pm 0.07, -0.1 \pm 0.3)$, or nearly a full magnitude redder. This is also similar to A0620−00, which 3 months after maximum light had $B - V = 135$ (Oke 1977). The galactic coordinates of Cen X-4 are $l^{II} = 332$, $b^{II} = 24$, so the interstellar reddening is very likely less than a few tenths of a magnitude (see also § II*e;* the compilation of Lucke [1978] gives $E_{B-V} \sim 0.2$ mag per kpc in this direction).

d) Rapid Variability

The data of Figure 2 indicate that the optical flux of Cen X-4 varies erratically from day to day in addition to its gradual decline. To search for more rapid variability we monitored the source with 0.1 s time resolution for six intervals of ~5–8 min each separated by similar observations with equal duration of a field standard. The observations were made on 21 May at the 1.5 m telescope with the RCA 31034A phototube and a $CuSO_4$ filter which gives an effective bandpass of ~3100–5500 Å. Cen X-4 shows clear variability of ~8% in ~15 minutes, which is not present in the intensity of the standard star. We investigated variability on shorter time scales by computing an autocorrelation function. The average autocorrelation function for Cen X-4 shows excess correlation for lag times $\lesssim 50$ s which is not present in the autocorrelation of the standard. This "flickering" can be modeled by aperiodic pulses with characteristic durations of ~50 s, intensities given by $f^2 d = 2.8 \times 10^{-4}$, where f is the fractional amplitude of the pulses and d is their duty cycle (pulse duration times repetition rate). For example, if $d = 10\%$ then $f = 5\%$. (The nearby, faint companions of Cen X-4 [see Fig. 1] are ~1% the intensity of Cen X-4 and were just outside the edge of our 10″ aperture, but may have caused some contamination. However, they are too faint to explain all of the flickering.) Flickering is seen in cataclysmic variables and in Sco X-1 (cf. Robinson and Nather 1979) and is thought to arise in an accretion disk. We also performed a Fourier analysis of the data to search for optical periodicities from Cen X-4. None were found, and we set a limit of <0.1% for the pulsed fraction over frequencies of 0.05–5 Hz.

e) Spectra

Various red and blue spectra were obtained by Linda Stryker on May 20 with an image-tube spectrograph on the Yale 1 m telescope, by Drs. Barry Lasker and Tom Kinman on May 23 with the SIT vidicon + RC spectrograph on the 4 m (Attwood *et al.* 1979), and by us on May 25, 26, 27, and 28 with the same 4 m system (these were flux calibrated in the usual manner [Osmer and Smith 1976]). All show strong blue continua with no absorption lines but with weak Balmer emission (with typical equivalent widths [e.w.] of 5 ± 1 Å for Hα, 1.0 ± 0.5 Å for Hβ, and 0.6 ± 0.2 Å for Hγ). There is also clear evidence of He II λ4686 emission (e.w. = 1.5 ± 0.5 Å) and of a broad blend at ~λ4640 (e.w. = 1.5 ± 0.8 Å), probably the N III (λλ4634.2, 4640.6, 4641.9) Bowen fluorescence lines (see below). These H, He II, and N III lines are characteristic of X-ray source counterparts in general (McClintock, Canizares, and Tarter 1975) and are particularly evident in the faint blue counterparts of persistent sources, bursters, and other soft X-ray transients (e.g., see Margon 1979; Canizares, McClintock, and Grindlay 1979*b;* Oke 1977; Whelan *et al.* 1977; Murdin *et al.* 1977; Griffiths *et al.* 1978; further references can be found in Bradt, Doxsey, and Jernigan 1979).

The most striking features of the blue spectra shown in Figure 3 are intense emission complexes between ~λ3775 and λ3850 and between λ3900 and λ3975. Emission near these wavelengths is present in the spectra of all three X-ray burster counterparts previously studied by us (Canizares, McClintock, and Grindlay 1979*b*). The emission complexes are not identical in all the bursters; those seen in 4U 1636−53 bear closest resemblance to the ones of Figure 3. For the bursters we argued that some of the emission was due to the O III Bowen fluorescence lines (λλ3754.7, 3757.2, 3759.9, 3774.0, and 3791.3). There are probably contributions from unidentified lines as well.

The N III λ4640 blend is generally attributed to X-ray heating driving the Bowen fluorescence mechanism (McClintock, Canizares, and Tarter 1975; Hatchett, Buff, and McCray 1976; Margon and Cohen 1978; Canizares, McClintock, and Grindlay 1979*b*), and the same process undoubtedly occurs in Cen X-4. Another N III line should appear at ~λ4100, but scaling from the burster spectra of Canizares, McClintock, and Grindlay (1979*b*) gives an equivalent width of only 0.4 ± 0.2 Å for this emission which we could well have missed. The O III emission at λλ3750–3790 is also expected from the Bowen mechanism, and as we discussed in the burster study the relative strength of these lines to the N III lines depends on the detailed velocity structure in the source. We note that the Bowen lines of O III at λλ3428, 3444 were seen in the spectrum of the optical counterpart to the X-ray transient A0620−00 by Oke and Greenstein (1977).

There is no evidence for interstellar absorption lines or bands in any of our spectra, nor would any be expected if $E_{B-V} \lesssim 0.8$ (Bromage and Nandy 1973). All the spectra show an unexplained dip in the continuum at ~λ4800 with a width of ~100 Å.

Wyckoff (1979) has reported that on July 15 faint Balmer, He II, and He I emission was present but that the λ4640 emission was not. The forbidden line [O III] λ4363 was moderately strong. Presumably the source was in a rather different state by this time, but a

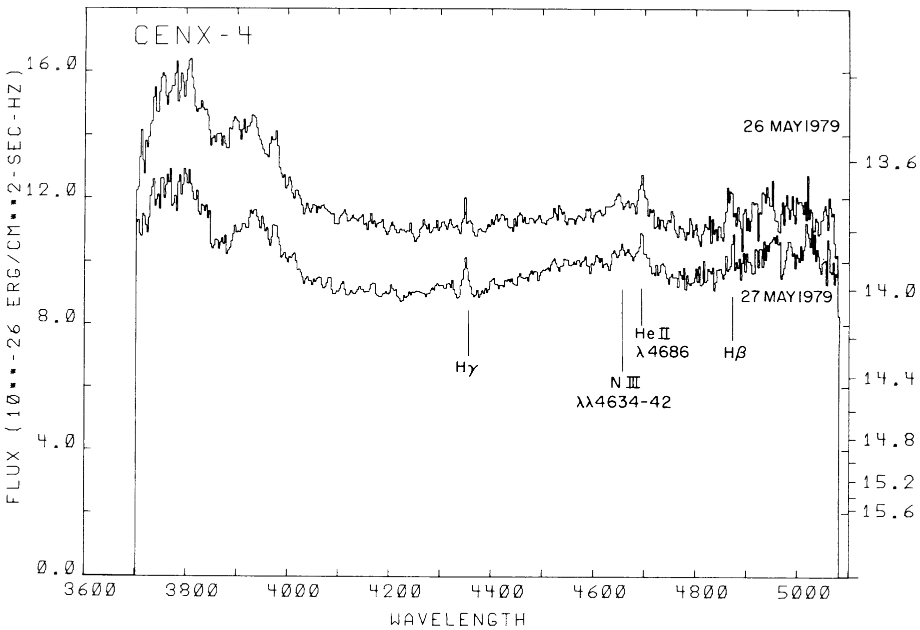

FIG. 3.—Two blue spectra of Cen X-4 obtained with the CTIO 4 m telescope, RC spectrograph, and SIT vidicon camera. The labeled features and the excess below λ4000 are discussed in the text.

comparison with our spectra must await publication of more details.

III. DISCUSSION

Cen X-4 is remarkable in that it exhibits the optical and X-ray characteristics of the class of soft X-ray transients on the one hand and those of X-ray bursters on the other.

Cen X-4 as a soft X-ray transient.—The class of soft X-ray transients is characterized by their intense outbursts, their X-ray temperatures of ~2–6 keV, and an absence of X-ray pulsations (e.g., Canizares 1976; Pounds 1976; Kaluziensky *et al.* 1977; Cominsky *et al.* 1978; Amnuel and Guseinov 1979). The optical counterparts to these transients brighten by several magnitudes during the X-ray outburst; show blue continua and weak He II λ4686, Balmer, and λλ4630–40 emission lines near maximum light; and are probably red while quiescent (e.g., see Whelan *et al.* 1977; Oke and Greenstein 1977; Oke 1977; Murdin *et al.* 1977; Griffiths *et al.* 1978). Cen X-4 meets the qualifications for membership in this class on the basis of its X-ray properties (Evans, Belian, and Conner 1970; Kaluziensky and Holt 1980) and its optical properties as reported in this *Letter*.

Cen X-4 as an X-ray burster.—Oda (1979) has reported the detection by the Hakucho satellite of a type I X-ray burst from Cen X-4. A burstlike flare lasting several minutes was detected in 1969 by Belian, Conner, and Evans (1972). Our optical spectra of the source resembles those of the counterparts of X-ray bursters, and in particular they show strong emission complexes at λλ3775–3975 which are very prominent in burster counterparts but have not been reported in other nonbursting X-ray source counterparts (see § II*e*). Thus if Cen X-4 were permanently endowed with the characteristics it exhibited during the last few days of 1979 May it would fit comfortably into the class of X-ray bursters (e.g., see Lewin 1979; Lewin and Clark 1979).

Therefore, Cen X-4 is a clear example of a soft, transient X-ray burster. The most important consequence of the connection between bursters and soft transients is the support it gives to the hypothesis that bursters are accreting neutron stars in binary systems (see reviews by Lewin 1979; Lewin and Clark 1979). The suggestion of a connection between bursters and transients in general was first made by Lewin *et al.* (1976) for the galactic center sources. MXB 1659−29 is a burster (Lewin, Hoffman, and Doty 1976) and a transient (Lewin 1978; Share *et al.* 1978; Doxsey *et al.* 1979). The rapid burst episodes of MXB 1730−335 are transient and recurrent (Grindlay and Gursky 1977; Lewin 1979) and there are other less secure candidates (Fabbiano and Branduardi [1979] review these). These associations of bursters with transients have already provided circumstantial evidence supporting the binary hypothesis (Lewin 1979; Fabbiano and Branduardi 1979), but there is a wide variety of transient behavior which may arise from a variety of physical situations. Cen X-4 is the first X-ray burster which is securely identified with a clearly defined class of transients—the soft transients of the A0620−00 type.

The evidence for the binary nature of A0620−00 and A1524−61 is presented by Matilsky *et al.* (1976), Oke and Greenstein (1977), Oke (1977), Whelan *et al.* (1977), and Murdin *et al.* (1977), and references therein. Probably the most compelling supporting fact is the spectrum of the cool secondary of A0620−00 which is detectable at minimum light (Oke 1977; the recurrent transient Aquila X-1 also has a cool secondary [Thorstensen, Charles, and Bowyer 1978]). The reddening of Cen X-4 as it fades suggests that it too has a cool secondary. Its magnitude at minimum makes it amenable to spectral classification so that the binary nature of Cen X-4 should be directly visible in the next observing season.

Finally, we note that the presence of optical flickering (§ II*d*) supports the hypothesis that at least some of the light is from an accretion disk. The Bowen lines (§ *IIe*) and the relation between the X-ray and optical fluxes (§ II*d*) suggest that X-ray heating plays an important role in the optical emission. Oke and Greenstein (1977) reached similar conclusions for A0620−00 on the bases of continuum shapes and energetics.

We are extremely grateful to the staff and visiting astronomers at CTIO who contributed their skill, observing time, and enthusiasm to this project. In particular, we thank Martha Liller, Linda Stryker, Barry Lasker, Tom Kinman, and Hugh Harris. We thank Ronald Remillard for observations at the McGraw Hill Observatory. The expert assistance of the night assistants and other supporting staff at CTIO is deeply appreciated. We are thankful for the rapid communication of the X-ray outburst by Steve Holt and Lou Kaluziensky facilitated by Barry Lasker and Nolan Walborn, and we also thank Kaluziensky and Holt for a prepublication copy of their X-ray light curve and for permission to use their data.

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CLAUDE R. CANIZARES and JEFFREY E. MCCLINTOCK: Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

JONATHAN E. GRINDLAY: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138