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NOVA OPHIUCHI 1977: AN X-RAY NOVA

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ABSTRACT

We report the observation by the *HEAO 1* satellite experiments of the X-ray nova in Ophiuchus discovered by Kaluzienski and Holt which we designate H1705−25. The SAO/MIT scanning modulation collimator has been used in conjunction with the NRL large-area sky survey to give two possible positions for the X-ray nova, each having errors of $0'.3 \times 1'.8$. We report the discovery of a 16.5 mag optical nova (Nova Ophiuchi 1977) in one of the error boxes, and we identify the X-ray source with the optical nova. We classify the object as being of the A0620−00 and A1524−61 type, i.e., a low-mass binary system.

Subject heading: X-rays: sources

I. INTRODUCTION

During the *HEAO 1* scans of the galactic hub X-ray sources in 1977 August–September, three bright transient sources were observed, viz., H1705−25, H1743−32, and 4U 1608−52; observations of 4U 1608−52 are described in an accompanying *Letter* (Fabbiano *et al.* 1978), and the position of H1743−32 has been reported by Doxsey *et al.* (1977).

We report here the observation and optical identification of the X-ray nova (or bright X-ray transient) in Ophiuchus, H1705−25 (Kaluzienski and Holt 1977*a;* Griffiths *et al.* 1977; Longmore *et al.* 1977). From preliminary observations presented here, the object seems to resemble the X-ray novae A0620−00 and A1524−61, both of which have been identified with optical novae. The main characteristics of this class of nova are: (i) increase in X-ray intensity by a factor of 100 or more, with a rise time of a few days and *e*-folding decay time of several tens of days, without short time scale variability; (ii) soft X-ray spectrum ($kT \sim 2$ keV); (iii) blue, almost featureless optical continuum in the early stages; and (iv) a ratio of X-ray to optical luminosities $L_X/L_{opt} \sim 10^2$.

The well-studied prototype of this class of X-ray novae, A0620−00, is thought to be in a low-mass binary system (Endal, Devinney, and Sofia 1976; Wu *et al.* 1976; Avni, Fabian, and Pringle 1976; Kaluzienski *et al.* 1977; Whelan *et al.* 1977; Oke 1977), with the optical emission arising partly from the accretion disk and partly by reprocessing of the accretion-disk X-ray emission by the dwarf companion of a neutron star.

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II. OBSERVATIONS

On 1977 September 8 an X-ray source was observed in quick-look data from the *HEAO 1* satellite, both in the NRL large-area sky survey (LASS) experiment and in the SAO/MIT scanning modulation collimator (MC) (Gursky *et al.* 1977), at a position not coincident with any previously cataloged source. It was immediately realized that the source was a bright X-ray transient, since its strength was at least several hundred *Uhuru* counts s^{-1}. The source had already been discovered and observed with the *Ariel 5* all sky monitor (Kaluzienski and Holt 1977*a*) from 1977 August 31, with a position determined to an accuracy of 1°. The source first appeared in data from the *Ariel 5* sky survey instrument on August 7.9 ± 0.5 and by August 10.0 had risen to an intensity of ~3 times that of the Crab Nebula (Watson, Ricketts, and Griffiths 1978).

From the few orbits of quick-look data available from *HEAO 1*, a preliminary position for the source was determined and communicated to the Anglo-Australian Observatory. Plates were taken on the night of September 10–11, both at the prime focus of the 3.9 m AAT as well as with the 1.2 m UK Schmidt.

The elevation (ecliptic longitude) of the source in the field of view (FOV) of the *HEAO 1* instruments was not known at the time of the initial sighting. The data obtained during the next several days from the NRL instruments (LASS) were therefore used to position the source to ~10′ accuracy in this direction as the source moved at ~1° per day through the 1° × 4° FWHM FOV of modules 1–4 and the 1° × 0°.5 FWHM FOV of module 5. In this manner, we determined an R.A. of $17^h4^m.5 \pm 0^m.8$ (meridians of R.A. have small inclination to ecliptic meridians in this region). The approximate ecliptic latitude was obtained from the analysis of individual transits of the source by the LASS and the MC (4° × 4° FOV). This analysis made use of the SAO/MIT fine-aspect solution obtained from the rate gyros and star-trackers. This led to a declination of −25°00′ ±

02′ from the LASS at the above R.A. and $-25°01' \pm 03'$ from the MC. Known sources within the scan circle at the time of observation of the X-ray nova, viz., 4U 1702−36 and 4U 1642−45, were used to calibrate the offsets between the LASS and the star cameras.

The MC data from two quick-look orbits (1977 September 9.17 and 10.15; all dates are UT) were summed to give the multiple lines of position from MC1 and MC2 shown in Figure 1. The possible positions for the source lie at the two intersections of the MC1 and MC2 lines which also lie within the LASS location errors. These positions are centered at $\alpha = 17^h05^m10^s.2$, $\delta = -25°01'21''$ and $\alpha = 17^h04^m01^s.5$, $\delta = -24°59'44''$. The lines of position have 90% confidence errors of 7″.0 for MC1 and 5″.6 for MC2, and these two sets of lines are inclined to each other at an angle of 20°.

The plates taken at the AAT on 1977 September 10.4 were searched in the region of these refined positions. The unfiltered IIa-O plate taken at the AAT prime focus, and the IIIa-J plate with GG385 filter taken with the 1.2 m UK Schmidt show the image of an optical nova at R.A. $17^h05^m10^s.4 \pm 0^s.2$, decl. $-25°01'38'' \pm 2''$ (1950.0) (Table 1, Fig. 2 [Pl. L3]). The magnitude of the star at discovery, $B = 16.5 \pm 0.5$, has been estimated by inspection of standard sequences on similar plates. A possible prenova star is visible right at the plate limit on glass copies of the red and blue Palomar Sky Survey plates (i.e., at $B = 21$, $R = 21$). It is also visible on the UK Schmidt survey plate of the area taken 1976 May 29. The variable star II Oph is 2′ NW of the nova.

TABLE 1

Optical and X-Ray Positions for Nova Ophiuchi 1977

	α(1950.0)	δ(1950.0)
Optical nova..........	$17^h05^m10^s.4 \pm 0^s.2$	$-25°01'38'' \pm 2''$
X-ray source position center..............	17 05 10.2	−25 01 20.6
Parallelogram corners..	17 05 09.60	−25 02 19.7
	17 05 09.32	−25 01 28.0
	17 05 10.78	−25 00 22.4
	17 05 11.06	−25 01 13.3

The optical nova was confirmed by Liller (1977), who measured approximately constant red magnitudes of 15.7 ± 0.5 on September 15.2, 18.1, and 19.1.

Spectra of the candidate star were obtained at the AAT on 1977 September 16.4 and September 22.4 (Fig. 3). A blue blazed grating was used, feeding the image photon-counting system at 140 Å mm^{-1}, with a resultant resolution of 2 Å. Both spectra show a continuum with no absorption lines detectable. Both, however, show an emission line (of 6 Å equivalent width) identified as λ4686 He II. There is no evidence for Hα emission or emission at the λ4640 complex (with upper limits of 2 Å equivalent width).

By comparison with spectra of white-dwarf standard stars, the color of the continuum was measured as $B - V = 0.64 \pm 0.10$ on September 16 and $B - V = 0.86 \pm 0.10$ on September 22. Although the formal error of these measurements is very small, past experience indicates that colors measured with the AAT's spectrograph are accurate only to 1/10 mag due to the effects of atmospheric dispersion on the image of a star formed on the spectrograph slit; the increase in reddening may be real, however.

The X-ray spectrum from the two quick-look orbits has been determined from the three-channel pulse-height analyzer of the MC to be

$$\frac{dN}{dE} = \frac{23 \pm 5}{E^{1.4}} \exp\left[-E/(3.0 \pm 0.5)\right]$$
$$\times \exp\left(-N_{\rm H}\sigma\right) \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}$$

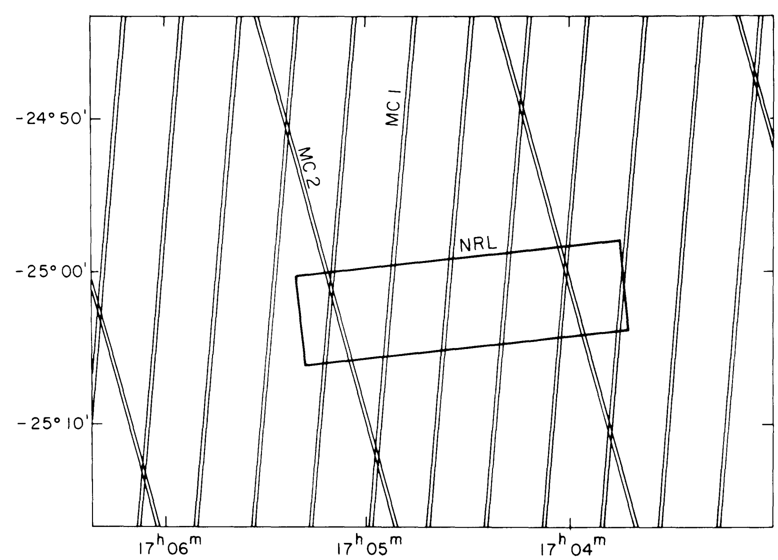

Fig. 1.—Lines of position for the X-ray nova H1705−25 from the SAO/MIT scanning modulation collimator (MC), and the NRL large-area sky survey instrument (LASS). Only two of the intersections of MC1 and MC2 lines lie within the NRL box. The optical nova was found at the easterly intersection.

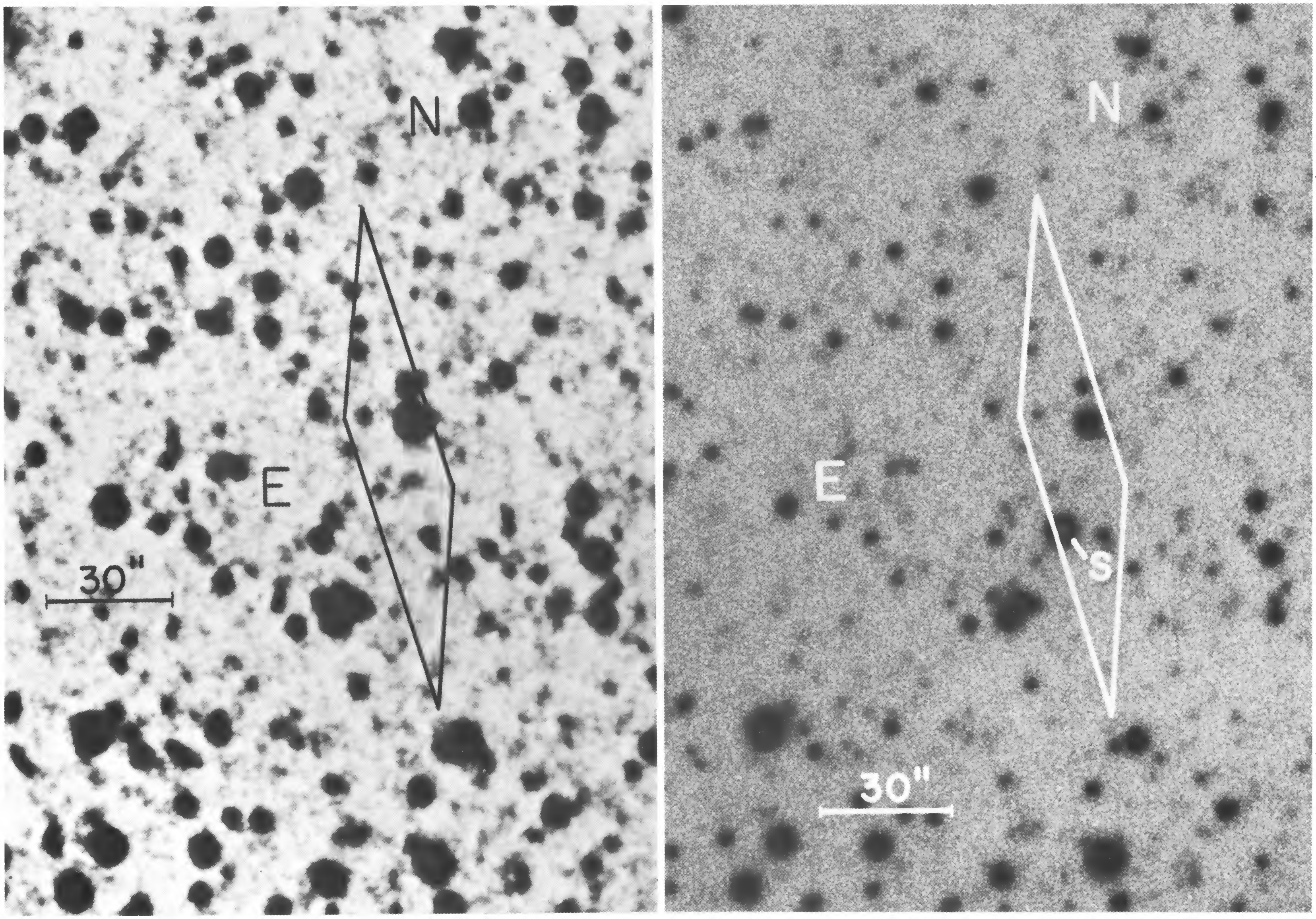

FIG. 2.—(*Left*) Reproduction of the red Palomar Observatory Sky Survey plate of the area near the nova. (*Right*) Print from the blue plate taken at the prime focus of the AAT on 1977 September 10 showing the optical nova, star S, and the error box for the X-ray transient (Table 1). A faint image at the position of S on the Sky Survey photograph can be seen on the original, although we do not expect it to be prominent on the printed reproduction.

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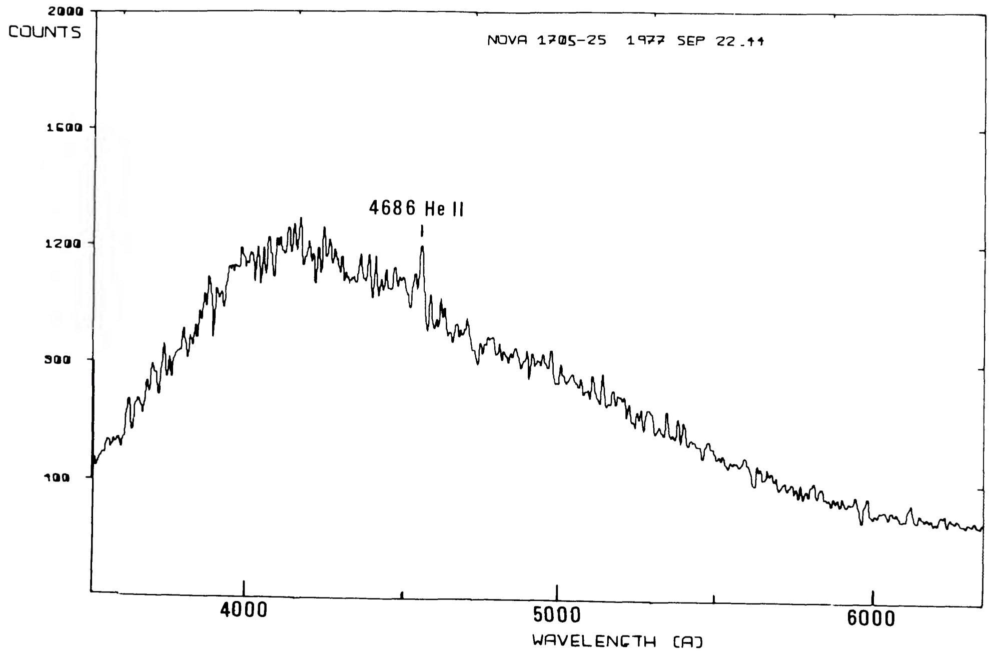

FIG. 3.—Optical spectrum of Nova Ophiuchi 1977, taken UT 1977 September 22.4 with the 3.9 m Anglo-Australian Telescope, smoothed to 5 Å resolution. The only real feature is the λ4686 He II emission line.

on the assumption of thermal bremsstrahlung emission, with the energy dependence of the Gaunt factor approximated as $E^{-0.4}$. This leads to $N_H = (3 \pm 1)10^{21}$ H atoms cm^{-2} where σ is the interstellar X-ray absorption cross section (Brown and Gould 1970).

A search through *Uhuru* data for the source, using the point-summation technique, resulted in a 3 σ upper limit of 1.5 *Uhuru* counts s^{-1} for the source during the *Uhuru* time base (1971–1973; Peters 1977).

III. DISCUSSION

The probability of a chance association of a galactic nova with the X-ray nova must be considered, since we are not aware of any plates taken of this region between 1976 May and 1977 September. Estimates of the number of novae per year per galaxy range from 26 to 100 (Plaut 1965), with 40 as an "accepted value" (Allen 1973). Most of these occur within 10° of the galactic center (Plaut 1965, Fig. 1), and decline by 3 mag in 10 to 300 days. We can adopt 0.1 years as the lifetime of visibility of an optical nova (Allen 1973). Thus the probability by chance coincidence that a galactic nova will appear on a given photograph within either of two areas of sky 1'.8 by 0'.3 situated near the galactic center is $\sim 4.10^{-6}$.

If the optical nova appeared at approximately the same time as the X-ray nova (August 8), the present observations were made about one month after maximum light. The identification of the X-ray nova is therefore also suggested by the optical spectrum, which has characteristics similar to those observed in the X-ray nova A0620−00 one month after maximum (Whelan *et al.* 1977). At first featureless, the optical spectrum of A0620−00 exhibited He II 4686 and the λ4640 complex 35 days after maximum, with no detection of Hα emission until two months later. The He II 4686 emission found in the present case is a characteristic feature of the optical spectra of several identified galactic X-ray sources (McClintock, Canizares, and Tarter 1975). We wish to emphasize that the optical spectrum for this object, as for A0620−00, does not resemble that of a classical nova.

The visual extinction has been estimated from the observed low-energy X-ray absorption (viz., $N_H = 3 \pm 1 \times 10^{21}$ H atoms cm^{-2}), to be $A_V \sim 1.4 \pm 0.5$ mag or $E_{B-V} \sim 0.5 \pm 0.1$, using the relationships between N_H and A_V or E_{B-V} established by Gorenstein (1975), Ryter, Cesarsky, and Audouze (1975), and Jenkins and Savage (1974). Independently, we can obtain an upper limit on A_V by assuming that the optical spectrum on September 16 ($B - V = 0.64$) was thermal, the star having cooled from a hot blackbody, like A0620−00 near outburst, and hence had an intrinsic color $(B - V)_0$ redder than −0.4. We thus deduce an upper limit on the interstellar reddening of the star as $E(B - V) \leq 1.0$ mag, i.e., $A_V < 3.3$ mag. At discovery on September 10 the magnitude was $B = 16.5$; corrected for interstellar absorption $A(B) = 4E(B - V)$, its magnitude would be $B \gtrsim 12.5$.

If the maximum X-ray luminosities of H1705−25 and A0620−00 are comparable (i.e., $\sim 10^{38}$ ergs s^{-1}), then the distance of H1705−25 must be ~3 kpc if A0620−00 is at ~1 kpc (Whelan *et al.* 1977; Oke 1977).

If we extrapolate our (optically thin) thermal bremsstrahlung spectrum into the optical regime, the observed optical flux falls ~4 mag below the extrapolated curve, and we can account for only part of this by the estimated interstellar extinction of ~1.4 mag. It is thus possible to account for the optical flux by extrapolation of the bremsstrahlung spectrum from an accretion disk which becomes optically thick in the infrared, like that of A0620−00 (Kleinmann, Brecher, and Ingham 1976; Griffiths, Ricketts, and Cooke 1976; Dilworth *et al.* 1977). We note, however, that some or most of the optical flux may come instead from the heated-up photosphere of the companion star and the heated-up outer parts of the accretion disk (cf. A0620−00: Avni *et al.*; Endal *et al.*; Whelan *et al.*; Oke and Greenstein 1977). The ratio of X-ray to optical luminosities in the present case is $L_X/L_{opt} \sim 10^2$.

H1705−25 is also very similar, as far as present observations allow us to comment, to the X-ray nova A1524−61, which reached an X-ray intensity approximately one-fifth that of H1705−25 and an optical intensity 1 mag fainter. (The optical identification by Murdin *et al.* 1977 has recently been strengthened by the 20″ radius error circle of *SAS 3* [Bradt *et al.* 1977]). A1524−61 has been compared with A0620−00 by Murdin *et al.* (1977), and all three sources clearly fall in the same class. Some of the other X-ray novae previously observed, such as 3U 1543−47, Cen X-2, and Cen X-4, probably belong in this class, on the basis of their soft spectra (Pounds 1976; Canizares 1976), but none of these has a well-established optical counterpart.

The observations presented here can be understood in terms of models of X-ray novae which invoke accretion from a late-type dwarf onto a neutron star. Arguments against white-dwarf models have been summarized by Whelan *et al.* Brecher, Ingham, and Morrison (1977) discuss the theory of shocked circumstellar gas as the radiation source, following the outburst of a classical or recurrent nova. They also summarize those observational facts which eliminate the model, which include the measured infrared flux and the lack of X-ray line emission (Griffiths, Ricketts, and Cooke 1976).

The two possible mechanisms of accretion onto a neutron star, as with other galactic X-ray binaries, are those of a Roche lobe overflow or a stellar wind. For A0620−00, Oke (1977) concludes that Roche lobe overflow is unlikely, since the optical spectrum 1.3 years after outburst was found to be that of a K5–K7 dwarf (together with the remains of an accretion disk) when the magnitude of the star had returned to its preoutburst value, and such a dwarf is unlikely to fill its Roche lobe unless the compact star is massive. Dynamical instabilities of stars in contact with their Roche lobes have been discussed by Bath *et al.* (1974), Bath (1975), and Wood (1977) as an explanation of dwarf novae and X-ray transients. Such a dynamical instability may be accompanied or enhanced by accretion-disk instability, possibly with some self-excited mass transfer (Arons 1973; Basko and Sunyaev 1973), following the initial X-ray outburst.

The alternative model of accretion by stellar wind has been discussed by Amnuel and Guseinov (1976) as an explanation for A0620−00 and A1524−61, with buildup of an accretion disk until an instability occurs. Weak X-ray emission is predicted from the quiescent-state system, and this model is therefore supported by observations of 4U 1543−47 and of 4U 1608−52, which has recently been observed as a transient (Kaluzienski and Holt 1977*b*; Clark and Li 1977; Fabbiano *et al.* 1978).

Since there have been no medium or high time resolution studies of this class of X-ray novae in the precursor or late stages of evolution, we have no direct evidence as yet for the presence of a neutron star or black hole in this class of X-ray novae. If the tentative identification of 4U 1608−52 with the Norma burster is correct, however (Grindlay and Gursky 1976; Fabbiano *et al.* 1978), and if this source is in the same class, this would be evidence for the presence of a neutron star or black hole in systems of this kind, with the short time scale variability observed while the source was not in a "bright transient" state.

Once the precursor stage of an X-ray nova is passed, the pulsating signature of the X-ray emission from the vicinity of a neutron star, or the millisecond variations in the X-ray flux from a black hole, may be lost by scattering in the accretion disk (which may be oblate, as suggested for A0620−00 by Griffiths, Ricketts, and Cooke 1976, from lack of X-ray polarization). We therefore encourage high time resolution observation of an X-ray nova in the precursor or late stages of evolution, in order to confirm the nature of the underlying compact object.

The AAT optical spectrum of September 16 was made by R. Cannon, M. Smith, and A. Boksenberg. M. Edmunds and C. Chun provided some of their AAT time to take the spectrum of September 22.

Several people have participated in the *HEAO 1* NRL effort, headed by H. Friedman (Principal Investigator). The following list is not complete but recognizes those whose contributions were most pertinent to this paper: E. T. Byram, T. A. Chubb, W. Evans, J. Meekins, and D. Yentis were involved in the instrument design, construction, and testing; D. McNutt and K. Wood in software development; and G. Share and H. Smathers in data analysis.

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