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A MODEL FOR THE X-RAY
NOVA A0620-00

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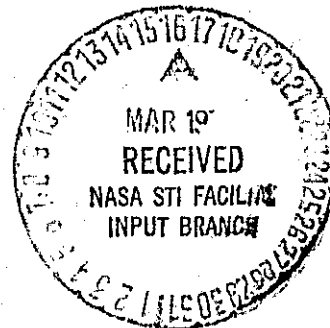
GODDARD SPACE FLIGHT CENTER
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A MODEL FOR THE X-RAY NOVA A0620-00

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ABSTRACT

We propose a model for the transient x-ray source A0620-00 involving a white dwarf accreting mass from a late-type subgiant companion. The transient behavior of the x-ray source is explained by the instability to mass loss of the companion (as in Algol-type binaries). The brightening, spectrum, and decay timescale of the optical counterpart are explained in terms of re-emission of x-radiation intercepted by the subgiant. A0620-00 should provide an excellent test case for numerical models of stellar atmospheres irradiated by an external x-ray flux.

INTRODUCTION

The transient x-ray source A0620-00 was discovered on August 3, 1975 by the Ariel-5 Sky Survey Experiment (Elvis et al., 1975a). Within two weeks, radio and optical counterparts had been identified. Within two months, extensive observations were available in the x-ray, UV, visual, IR, and radio wavelength bands, including the discovery of a previous outburst in 1917 recorded on Harvard Patrol plates. The chronology and reference for these observations are given by Maran (1976). Although we will be discussing the observations in detail in connection with a model for the source, we find it convenient to present a brief summary of the observations here, for orientation purposes.

X-ray

A short-lived precursor peak followed by a rapid rise to maximum. Decay from maximum characterized by an e-folding time of $\sim 27^d$ (Bradt and Matilsky, 1976; the decay was not strictly exponential so a range in e-folding times have been measured; 27^d is a typical value). Initially hard, then softening, spectrum.

Optical

Not observed prior to x-ray maximum. Brightest observed apparent magnitude ~ 11.2 (French, 1975). Optical light decay with e-folding time $\sim 69^d$ and some evidence for a 4^d modulation (Duerbeck and Walter, 1976; as with the x-rays, the decay is not strictly exponential, leading to a range in e-folding times and we quote a typical value). The source spectrum was initially featureless, even at high dispersion, with some lines appearing in emission approximately one month after x-ray maximum. The pre-outburst

object was red, with $M_B \simeq 18$ (estimated from Palomar Sky Survey Plates).
An earlier brightening occurred in 1917, with no major intervening events
(Liller, 1975).

Radio

Rapidly decaying source with flat spectrum associated with early phases
of x-ray outburst.

COMPARISONS TO CLASSICAL NOVAE

The optical photometric behavior bears some resemblance to that
of a classical recurrent nova. The amplitude and time interval between out-
bursts fits the Kukarkin-Parenago relation. The typical recurrent nova has
$M_v \sim 7.5$ at maximum and this would imply a distance of 5.7 kpc (with 1 mag/kpc
absorption). The absolute magnitude-decay rate data for novae (McLaughlin,
1960) predicts a similar distance, though there seems to be some confusion
on this point in the literature on A0620-00 (see Endal et al., 1976). The
x-ray luminosity implied by these arguments ($L_x \sim 4.3 \times 10^{39}$ erg/s) is
extremely large but, since we have no previous x-ray observations of a
recurrent nova, this does not appear to be a fatal point, at first inspection.

The nature of the optical spectrum, however, rules out the association
of A0620-00 with classical recurrent novae. According to McLaughlin (1960),
"All novae near maximum have strong, shortward displaced absorption
spectra...". More or less featureless spectra are associated with the
quiescent stage of novae, but never with an outburst. After maximum, broad
emission lines always appear, leading to the classical signature of an
expanding shell. However, spectra of the optical object associated with
A0620-00 taken near maximum show no lines intrinsic to the source (Gull and

York, 1975). Stellar lines (in emission) did not appear until more than three weeks after maximum (Peterson et al., 1975). Furthermore, the v-ray luminosity (several orders-of-magnitude larger than the optical luminosity) is incompatible with the theoretical models of novae (Starrfield et al., 1974), which predict little direct x-radiation from the outburst. The kinetic energy of the outflowing gas is also insufficient to provide the x-ray flux by shock processes. These predictions are confirmed by observations of Nova Cygni 1975, which produced no detectable x-rays even though the apparent magnitude at maximum reached $+2^m$ (Holt, 1975). Finally, the radio characteristics of A0620-00 are not nova-like in that the data are consistent with the radio flux peaking near x-ray maximum and decaying with an e-folding time of 5.2^d (Davis et al., 1975). For classical novae, the radio flux varies on timescales of months or years and actually increases with time after optical maximum (Wade and Hjellming, 1971). The above arguments constitute a strong case for not associating A0620-00 with classical novae.

A0620-00 AS AN ACCRETION SOURCE

If a classical nova is ruled out as a model for A0620-00, a logical alternative is a model driven by the mechanism which powers most other non-extended x-ray sources, i.e., accretion onto a compact object from a binary companion. In this case, the observations place stringent constraints on the nature of both the compact object and its companion.

Distance Indicators and Implications

As a zero-order distance indicator, we can use the observed color and deredden it to the high temperature saturation value [(B-V) $\simeq$ $-0^m.4$]. Then the observed color, (B-V) = 0.1 (Duerbeck and Walter, 1976), indicates

$E_{B-V} \lesssim 0\overset{m}{.}5$ or $A_V \lesssim 1\overset{m}{.}5$. Assuming 1 mag/kpc absorption leads to a distance
$R \lesssim 1.5$ kpc. Of course, this limit would not be correct if the object
lies in a direction of anomalously small interstellar absorption, though
one would not expect this from the galactic latitude. A better distance
indicator is provided by the ANS observations of the UV flux from A0620-00.
The depth of the 2200 $\overset{o}{A}$ interstellar absorption feature has been shown to
be well-correlated with distance and, for A0620-00, the derived distance is
$R \simeq 1$ kpc (Wu and van Duinen, 1976). A third distance estimate is provided
by the high resolution (optical) spectra of A0620-00, which show sharp inter-
stellar Na I D lines. From comparing the velocities and strengths of these
lines with 21-cm maps of the same region of the sky, a distance of $1 \leq R$
(kpc) ≤ 3 is expected (Snow et al., 1976). The lower limit corresponds to the
distance of a spiral arm with the same radial velocity as the Na I D lines
seen in the spectra of A0620-00 and the upper limit to the distance of a spiral
arm whose Na I D lines are not seen. The peak observed x-ray flux above
1 keV corresponds to a luminosity $L_x = 1.3 \times 10^{38}$ [R (kpc)]^2 erg/s (Elvis
et al., 1975b). For accretion at the Eddington limit onto a compact object
of mass $\simeq 1\ M_\odot$, this implies $R \simeq 1$ kpc, consistent with the above distance
estimates.

From the Palomar Sky Survey plates, we estimate the pre-outburst appa-
rent magnitude to be $M_B \simeq 18$. Assuming $R \lesssim 1.5$ kpc (the upper limit from
dereddening to B-V saturation) and 1 mag/kpc absorption, the absolute mag-
nitude is $M_B \geq 5.64$. Comparison of the red and blue PSS plate images indicates
a color corresponding to a spectral type K or later (assuming $\lesssim 0\overset{m}{.}5$ of redde-
ning). This implies that the companion to the compact object is a dwarf or
subgiant of mass $< 1\ M_\odot$. This rules out a black hole or neutron star for

the compact object due to the well-known difficulty in forming such objects
in binary systems of low-mass without disrupting the system (Blaauw, 1961).
The picture we have, then, is of a white dwarf orbiting a K dwarf or
subgiant, the latter nearly filling its Roche lobe and sporadically spilling
material onto the former. Accretion onto the white dwarf provides the
x-radiation and, as we will show below, x-rays intercepted and reradiated
by the K star can explain the characteristics of the optical brightening.

The Temperature and Luminosity of the Optical Outburst

We have two direct measures of the temperature of the optical radiation
during the outburst, based on the UV flux measurements reported by Wu
and van Duinen (1976) and on the optical spectra obtained by Snow et al.
(1976). According to Wu and van Duinen, the dereddened UV flux distribution
can be fit by a black body spectrum at 28,000°K. Snow et al. state that the
flux distribution from 4250 to 7400 Å resembles that of an O star with a
possible UV excess. This indicates a slightly higher temperature than that
suggested by Wu and van Duinen but this discrepancy and the UV excess can
be explained by the large amount of reddening ($E_{B-V} = 0^m.9$) assumed by Snow
et al. As we noted earlier, the largest excess allowed by the observed
(B-V) is $E_{B-V} \simeq 0^m.5$.

The brightest visual apparent magnitude reported during the outburst was
$11^m.2$. Applying the bolometric correction appropriate to the temperature
derived by Wu and van Duinen gives $m_{bol} = 8.4$ The corresponding optical
luminosity is

$$L_{opt} = 3.3 \times 10^{36} \ R^2 \ erg/s, \qquad (1)$$

where R is in kpc and $A_V = 1^m.0$ has been assumed. If the K star fills its
Roche lobe, the solid angle it subtends, as viewed by the white dwarf, is

$0.44 \geq \Omega$ (steradians) ≥ 0.12 for $\geq M_K/M_{w.d.} \geq 0.1$, where M_K and $M_{w.d.}$ are the masses of the K star and of the white dwarf, respectively (Kopal, 1959). The rate at which the K star absorbs x-radiation is $L_A = (\Omega/4\Pi) L_X$ or

$$L_A = (4.6 - 1.2) \times 10^{36} R^2 \text{ erg/s.} \qquad (2)$$

This radiation will be thermalized and reradiated at optical wavelengths. Comparison of equations (1) and (2) shows that enough x-radiation is intercepted by the K star to explain the optical brightening.

In addition to the observational evidence on the temperature of the optical counterpart, we have two model-dependent estimates. Using the estimate for the amount of x-radiation absorbed by the K star in equation (2), the effective temperature needed to reradiate this energy is

$$T_{eff} = 4.2 \times 10^4 \left(\frac{R}{r}\right)^{1/2} \left(\frac{\Omega}{f}\right)^{1/4} \quad °K, \qquad (3)$$

where r is the radius of the K star in solar units and f is the fraction of the total surface heated by the x-ray source. With $R = 1$ kpc, $r = 1 R_\odot$, $f = 0.5$, and $\Omega = 0.32$ [the value needed to bring equations (1) and (2) into exact agreement], we get $T_{eff} = 38,000°K$. Considering that the temperature derived by Wu and van Duinen is based on observations obtained some time after x-ray maximum and the uncertainties in the parameters in equation (3) (especially in r), the agreement is excellent.

The effective temperature is proportional to $(L_X)^{1/4}$ and decays with an e-folding time four times that of the x-ray flux. The x-ray e-folding time is $\sim 27^d$ so

$$\partial \ln T_{eff}/\partial t = -1/108 \ d^{-1} \qquad (4)$$

The e-folding time for the optical radiation at $\lambda \approx 4330$ Å (effective B magnitude wavelength for O stars) is $\sim 69^d$.

$$\partial \ln B_{4330}/\partial t = -1/69 \quad d^{-1} \tag{5}$$

Combining equations (4) and (5) gives

$$\partial \ln B_{4330}/\partial \ln T_{eff} = 1.57 \tag{6}$$

If we assume that the optical radiation can be approximated as a Planck function, it is easy to show that

$$\partial \ln B_{4330}/\partial \ln T_{eff} = \frac{3.33}{T_4} \left[1-e^{-3.33/T_4}\right]^{-1}, \tag{7}$$

where $T_4 = 10^{-4} T_{eff}$. Using the value of $\partial \ln B_{4330}/\partial \ln T_{eff}$ from equation (6) in equation (7) gives $T_{eff} = 34,000°K$ as an average temperature implied by the difference in e-folding times for the x-ray and optical fluxes. Again, the agreement with the observed temperature is excellent.

We should warn against interpreting the temperatures cited above too broadly. The temperatures indicated by the flux distribution and derived from model-dependent considerations characterize the continuum of the optical radiation and are not necessarily related to the ionization temperature of the K star atmosphere. The observed x-radiation from the compact object is very soft and will, therefore, be absorbed high in the photosphere of the K star, in a region optically thin for continuous optical radiation. For low x-ray fluxes, such a situation gives rise to an emission line spectrum (cf. Basko and Sunyaev, 1973). For the large x-ray flux of A0620-00, however, the ionization balance will be dominated by x-ray photoionization and the ionization temperature will be considerably higher than the temperature estimates discussed above. As a result, the emission will be dominated by continuous (free-free and recombination) mechanisms, which is consistent with the observed featureless spectrum. As the x-ray flux decreased, weak emission lines did, in fact, appear. Although the primary soft x-rays will be absorbed

well above the photosphere, the depth of the heated region will be increased somewhat in the process of degrading the radiation to UV and optical wavelengths. Without detailed atmosphere calculations (such as those of Basko and Sunyaev but with much larger incident fluxes) we cannot estimate the depth of the heated region. It is, however, possible that the region is optically thick to UV and optical radiation. If the inclination of the system differs considerably from 90° (as implied by the lack of absorption of soft x-rays by the accretion disk) the optical thickness along the line of sight to the observer will be increased by geometric effects. In summary, although the situation is rather complex, the spectral characteristics and behavior of A0620-00 are not inconsistent with the model we have proposed.

Temporal Behavior of the Source

As we have shown, the observations indicate that the system consists of a K dwarf or subgiant sporadically transferring mass to a white dwarf companion. The behavior required here is reminiscent of the behavior of Algol-type binary systems. Such systems, consisting of a late-type subgiant orbiting a main sequence star, often undergo sudden period changes indicating sporadic transfer of mass from the subgiant to the main sequence star. Presumably, the sporadic mass transfer is related to some (poorly understood) instability of the convective envelope of the subgiant. Not only is the time interval between outbursts of A0620-00 (58 yrs.) easily accommodated in this picture, but the mass loss rate implied by period changes in Algol-type systems is large enough to power the observed x-ray luminosity. For instance, the Algol-type system U Cephei went through two major (sudden) period changes in a 50 year interval [Biermann and Hall (1973)] with implied mass ejection rates of the order of $10^{-4} M_\odot$/yr. (see Figures 1 and 2 of Biermann and Hall). For a white dwarf of mass ~ 1 $M_\odot$, the accretion rate required to reach the Eddington limit

is about $10^{-5}M_{\odot}/yr$.

The mass ejected by the subgiant would form a disk around the white dwarf and be accreted as its angular momentum is dissipated by viscous forces. Since the ejected mass would have a finite range of angular momentum, this leads to the obvious speculation that the x-ray precursor was due to an initial infall of low angular momentum mass directly onto the white dwarf. If so, this would account for the hard x-ray spectrum of the precursor as compared to the spectrum near and after x-ray maximum. Again, it is interesting to speculate that the radio emission detected early in the history of the outburst was associated with the instability that caused the sudden mass transfer. The flat radio spectrum is very similar to that observed in binary star radio sources, which are well represented with subgiant active members. It may well be that the subgiant is the source of the radio emission.

Duerbeck and Walter (1976) observed a 4 day modulation in the optical light curve of A0620-00. If this is associated with an orbital period, it implies a semi-major axis of ~ 11 $R_{\odot}$, for a total system mass of ~ 1 $M_{\odot}$. This is somewhat larger than a typical subgiant radius (generally a few solar radii). However, as Duerbeck and Walter have noted, the observed modulation period may be a multiple of the true period, since the observations were taken at the same time each night. In addition, if the subgiant is the less massive component of the system, this would decrease the size of its Roche lobe and, hence, its required radius.

SUMMARY AND CONCLUSIONS

The observations of A0620-00, spanning the spectral range from x-rays to radio waves, place stringent constraints on the nature of the object and the cause of the outburst. A0620-00 is not a nova. If it is an accretion source,

the red color of the pre-outburst object, combined with constraints on
interstellar reddening due to the blue color observed during the outburst,
require that the companion to the compact object be of late spectral type.
A red giant or supergiant is ruled out by the distance indicators and the
requirement, in an accretion model, that the x-ray luminosity satisfy the
Eddington limit (a giant of $M_V \sim 0.0$ would require a mass for the compact
object $> 100\ M_{\odot}$). This implies that the companion is a late-type dwarf
or subgiant of low mass and, because of the Blaauw mechanism, that the
compact object is a white dwarf. The luminosity, temperature, and decay
timescale of the optical outburst associated with the x-ray event are consis-
tent with the optical brightening being due to a "reflection" effect. By
analogy with Algol-type binaries, the long-term behavior of A0620-00 is under-
standable. In summary, the model we have presented accounts, in a simple
way, for the behavior of A0620-00.

If the essential features of our model are correct, then A0620-00 could
provide an excellent opportunity for testing calculations of stellar atmos-
pheres irradiated by soft x-rays. As the x-ray luminosity decreases (in
effect, varying one of the input parameters for the calculations), changes in
the optical spectrum should provide an ideal test case for numerical models.
For this reason, continued monitoring of the optical spectrum is crucial.

Finally, the x-ray observations indicate that A0620-00 is an example of
the type of transient x-ray source classified by Canizares (1975) as an x-ray
nova. The discovery of an earlier outburst rules out the model for such
sources proposed by Van Horn and Hansen (1974) since they require that the
accretion rate onto the neutron star be slow enough that $10^6 - 10^7$ years
elapse between successive outbursts. The lack of confirmed optical counter-
parts for previous x-ray novae is not surprising, as can be seen from Table I.
We have estimated the distances and apparent visual magnitudes of the earlier

x-ray novae by comparison of observed x-ray fluxes with the observed para-
meters of A0620-00. For 3U1543-47, no optical counterpart was found down to
m_v = 15 (Matilsky et al., 1972). Our predicted brightness is less than
this. For Cen X-2 and Cen X-4, no systematic searches for optical counter-
parts were made. If plates of these regions taken during the x-ray phases
exist, it might be interesting to compare them with plates taken at other
times.

We would like to thank Dr. Warren Sparks for valuable discussions of
the classical nova outburst.

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TABLE I

Estimated Distances and Apparent Magnitudes for X-ray Novae*

Designation	Observed x-ray Flux(erg/cm^2-s)	Estimated Distance (kpc)	m_v during X-ray Phase	m_v during Quiescent Phase
A0620-00	10^{-6}	1	11.2	18
3U1543-47[†]	3×10^{-8}	6	20	27
Cen X-2	10^{-7}	3	16	22
Cen X-4	4×10^{-7}	1.5	13	19

*Distances estimates by assuming $L_x \approx 1.3 \times 10^{38}$ erg/s.

Apparent magnitudes estimated by comparison with A0620-00 and assuming 1 mag/kpc absorption.

[†]Lupus x-ray nova.