THE ASTROPHYSICAL JOURNAL, **214**:418–422, 1977 June 1

A SOFT X-RAY IMAGE OF THE ALGOL REGION

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Received 1976 September 28

ABSTRACT

Algol (β Persei) has been detected in two separate exposures of an imaging X-ray telescope. The 0.15 to 2 KeV X-ray luminosity is $\sim 2 \times 10^{30}$ ergs s^{-1}. The X-ray flux is interpreted as thermal emission produced by the direct accretion of mass from the K star to the B8 member of the triple star system.

Subject headings: stars: accretion — stars: eclipsing binaries — stars: individual — X-rays: binaries

I. INTRODUCTION

Algol has recently been detected by the SAS-3 rotating modulation collimator experiment (Schnopper *et al.* 1976) as a source of 2–6 keV X-rays. Previous efforts to observe X-rays from the triple star system (Canizares *et al.* 1973; Kifune, Wolff, and Weisskopf 1975) had resulted in upper limits somewhat below the SAS-3 observation. The present measurements, which extend the spectral data downward to 44 Å, confirm that Algol is an X-ray emitter and suggest variability, since the observed luminosity is about an order of magnitude below that measured by SAS-3.

In §§ II and III the current observations are described. Section IV discusses two mass-transfer models which may account for the X-ray emission.

II. EXPERIMENT

The soft X-ray telescope used in these observations was flown aboard Aerobee 350 rockets launched from the White Sands Missile Range on 1975 March 15 at 04:10 UT and on 1975 December 6 at 06:05 UT. The instrument, described previously by Gorenstein *et al.* (1975), consisted of two orthogonal, one-dimensional, grazing incidence mirrors and an imaging proportional counter at the focal plane of the telescope. The effective area of the mirror is ~ 150 cm^2 at a mean wavelength of 12 Å or 1 keV, and the instrumental resolution obtained was $4' \times 4'$.

III. RESULTS

Figure 1 is a 25 s exposure of a $2° \times 2°$ field around β Per. This December exposure was obtained while the rocket was locked onto Algol in order to update the attitude control system for subsequent maneuvers to other targets. Counts observed in the 0.5 to 1.5 keV band are displayed in image elements of $4'$ by $4'$. The average number of counts in the image (with Algol excluded) is 0.13 per element, while 9 counts are obtained for the element centered on the position of β Per. Hence, the probability that the counts attributed to Algol are due to random (Poisson) fluctuations is negligible ($\sim 10^{-13}$). A total of 44 net counts was obtained from Algol over the 0.15 to 2 keV band, corresponding to a luminosity of $\sim 2 \times 10^{30}$ ergs s^{-1} at the distance of β Per (30 pc, Bachmann and Hershey 1975).

An exposure of 4 s was obtained during a similar update maneuver during the 1975 March 15 flight of the same X-ray telescope. The Algol image has six photons at the position of β Per and a negligible counting rate elsewhere. The luminosity deduced from this measurement is consistent with that of the December measurement.

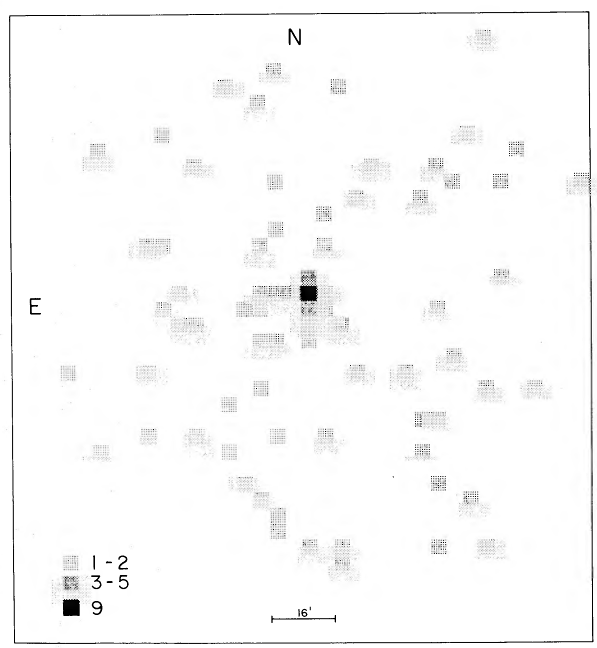

FIG. 1.—X-ray image of a $2° \times 2°$ field containing Algol (β Per), obtained from a 25 s exposure taken 1975 December 6. North is at top and the scale of this 0.5 to 1.5 keV image is indicated by the 16′ tick.

TABLE 1

X-Ray Observations of Algol

Date	Experiment	Phase	Luminosity* (10^{30} ergs s^{-1})	Energy Band (keV)
1975 Mar. 15...........	Imaging rocket†	0.37	2 (+1, −0.7)	0.15–2
1975 Oct................	SAS-3‡	0.35–0.55	16 ± 1.8	2–6
		0.9 –0.15	< 6	6–11
1975 Dec. 6.............	Imaging rocket†	0.52	2 ± 0.5	0.15–2
			0.2	0.15–0.28
			1.5	0.5 –2.0

* Distance = 30 pc (Bachmann and Hershey 1975). The indicated errors are statistical only. Estimated systematic uncertainties of 30% and 50%, for the rocket and SAS-3 values, respectively, have *not* been included above.

† See § II.

‡ Schnopper *et al.* 1976.

The energy flux has been computed for two energy bands, converted to luminosity, and is listed in Table 1. These flux values were computed by folding an assumed source spectrum through the instrumental response to predict the observed counting rate and then integrating the intrinsic spectrum over each energy band to obtain the tabulated values (which are rather insensitive to the actual parameters of the assumed spectrum). Also given in Table 1 is the SAS-3 result. Taken by themselves, the SAS-3 data (which were obtained at several phases throughout the 2.87 days orbital period) or the rocket measurements (taken at phases 0.37 and 0.52 for the March and December observations, respectively) are formally consistent with a constant source intensity. However, when the SAS-3 result is compared with the flux measurements from the present experiment, source variability seems quite likely. Although systematic uncertainties for the two experiments are rather large ($\sim 30\%$ for the rocket, $\sim 50\%$ for SAS-3), they do not explain the difference in flux.

The 0.15–0.28 keV flux (see Table 1) detected in the present observations rules out an explanation of the discrepant luminosity measurements solely in terms of a low-energy cutoff. Model spectra with enough (intrinsic) photoelectric absorption to reconcile the 2–6 keV emission with the 0.5–2 keV emission would leave no detectable flux in the 0.15–0.28 keV band.

The limited spectral information implies that the temperature was less than 30 million kelvins during the SAS-3 measurement, and greater than ~ 3 million kelvins for the two imaging rocket measurements.

IV. DISCUSSION

In this section we discuss general models for the X-ray emission from Algol based on mass transfer, either in a wind or by Roche lobe overflow. The discussion will suggest characteristic properties for the source, but more extensive observations and refined theory will be necessary for a definitive picture.

If it is assumed that the X-rays are produced in an isothermal plasma, the emission integral $\int N^2 dV$ necessary to produce the observed X-ray luminosity $L_x(\Delta E)$ in a band ΔE can be computed from

$$L_x(\Delta E) = P(\Delta E, T) \int N^2 dV\,, \tag{1}$$

where $N^2 P(\Delta E, T)$ is the emissivity of a hot plasma. Using the calculations of Raymond, Cox, and Smith (1976) for $P(\Delta E, T)$, we find that the emission integral required to fit the rocket observations ($\Delta E = 0.15$–1.5 keV) increases monotonically with the assumed temperature and is in the range

$$10^{53.0} \leqslant \int N^2 dV \leqslant 10^{53.7}\ \mathrm{cm}^{-3}\,,$$

for temperature in the range 3 to 30 million kelvins. The corresponding luminosity integrated over all energies is $L_x \sim 10^{31}$ ergs s^{-1}, roughly independent of temperature.

The emission integral required to fit the SAS-3 results ($\Delta E = 2$–6 keV) decreases monotonically with temperature in the 3 to 30 million kelvin range. (This is because these data refer to a higher energy band.) We find

$$10^{56.2} \geqslant \int N^2 dV \geqslant 10^{54.4}$$

for the same temperature range. The luminosity integrated over all energies is in the range 10^{34} to 10^{32} ergs s^{-1}.

The large difference in emission integrals derived to fit the two sets of data is evidence for variability; but in view of the systematic uncertainties in the measurements and the allowed range of temperatures, the evidence for variability cannot be considered conclusive.

An obvious model for the X-ray emission involves mass transfer between the close eclipsing pair of stars in the Algol system. (The parameters for Algol [Hill *et al.* 1971] are listed in Table 2.) The third member of the system, an A-type dwarf, orbits the close pair at a large distance and is, therefore, unlikely to have anything to do with the X-ray emission.

TABLE 2

PROPERTIES OF ALGOL*

A.

Property	*A–B*	*AB–C*
Period	2.87 days	1.9 years
Separation	14 $R_\odot$	600 $R_\odot$
Inclination	81°.6	...

B.

Component	$M/M_\odot$	$R/R_\odot$	T (K)	$L/L_\odot$	Spectral Type
A	3.7	3.0	10700	120	B8 V
B	0.8	3.4	4600	5	K IV
C	1.7	1.5	8300	10	A V

* Hill *et al.* 1971.

If it is assumed that the source is located at the surface of the B8 star, and that its size is characterized by the scale height

$$H_x \approx 1.2 \times 10^{11}\, T_7 \text{ cm}, \quad (2)$$

where T_7 is the temperature in units of 10^7 K, then the density

$$N_x \approx 3 \times 10^9\, T_7^{-3/2} \text{ cm}^{-3} \quad (3)$$

for the rocket observations.

The X-ray luminosity resulting from this process would be

$$L_x \approx \dot{M} v^2 \text{ ergs s}^{-1}, \quad (4)$$

where $\dot{M}$ is the mass-transfer rate and v is the characteristic velocity which is of the order of 500 km s^{-1}, the free-fall velocity onto the B8 star. A mass transfer of $\sim 10^{16}$ g s^{-1}, or $\sim 10^{-10}\, M_\odot$ yr^{-1}, is sufficient to power the source.

The visible B8 dwarf seems normal, as does the invisible K subgiant. The secondary by mass is in a later evolutionary stage than the primary, as is typical of Algol-type doubles. This can be explained by assuming that the secondary has lost a large amount of matter to the primary in the course of stellar evolution (Crawford 1955). The model of Hill *et al.* (1971) indicates that the 3.4 $R_\odot$ radius of the secondary is approximately equal to its critical radius of 3.45 $R_\odot$. This conclusion is dependent upon the ratio of the masses of the two stars, which is known only from indirect considerations, since the K star is not visible spectroscopically. There is no evidence for a high rate of mass transfer in Algol, but the K star could be transferring mass by Roche lobe overflow on a slow (nuclear) time scale following reversal of the mass ratio (see Paczyński 1971 and references therein). Although Algol occasionally displays activity indicative of gas flow (such as the appearance of emission lines), the actual rate of mass transfer is uncertain. Deduction of the rate of change of period is complicated by the three-body system and the existence of apsidal motion (see Hill *et al.* 1971).

Alternatively, the system may be transferring mass only by a stellar wind. As will be seen below, it should be possible to distinguish between these possibilities by observing Algol at different phases.

a) *Roche Lobe Overflow Model*

To simulate overflow of the Roche lobe, the procedure described by Flannery (1975) was used to calculate particle trajectories in the restricted three-body approximation for gas leaving the surface of the K star at a thermal velocity, about 7 km s^{-1}, from the inner Lagrangian point L_1. As illustrated in Figure 2, the stream intercepts the B8 star at an angle of 43° with respect to the line of centers and with a velocity of 470 km s^{-1}. The derived potential drop is 1.1 × 10^{15} ergs cm^{-1}. No disk or ring would be formed, since the specific angular momentum of the infalling material would sustain rotation only at a radius less than that of the B8 star.

Shock-wave heating will result (Landau and Lifshitz 1959) in a temperature, T, of the infalling matter

$$T = 1.4 \times 10^{-9} v^2 = 2.9 \times 10^6 \text{ K},$$

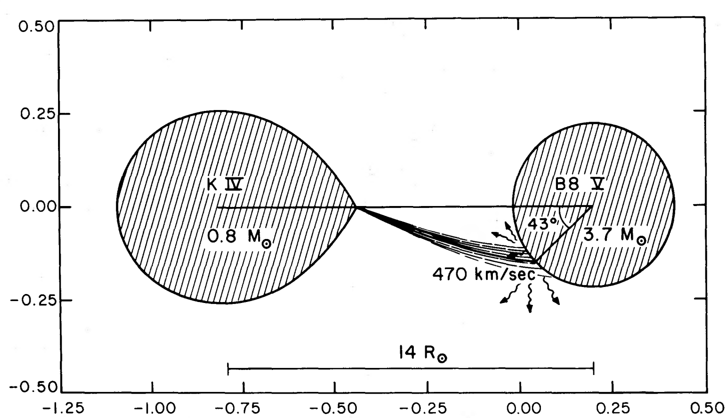

FIG. 2.—Restricted three-body trajectory corresponding to Roche lobe overflow in Algol—viewed in the orbital plane

for a mean atomic weight of 0.6. In view of the uncertainty in the mass ratio, the temperature could easily be a factor 2 higher.

An approximate location of the shock front formed by the impacting gas can be obtained by setting the ram pressure ρv^2 in the stream equal to the atmospheric pressure $P_{\rm atm}$ of the B8 star:

$$P_{\rm ram} \approx \rho v^2 \approx \dot{M}v/A = P_{\rm atm} , \qquad (5)$$

where ρ is the density and A is the cross-sectional area of the stream. If it is assumed that the streaming gas is isothermal with a temperature of 10^4 K and in hydrostatic equilibrium perpendicular to the orbital plane, then $A \approx 10^{21}$ cm^2 and $\rho v^2 \approx 5 \times 10^2$ dyne cm^{-2}. The atmospheric pressure P_0 for a B8 V star is 1.6×10^3 dyne cm^{-2} at the photosphere, and increases rapidly with optical depth (Allen 1973), so the shock will form just above the photosphere. The hot gas will expand to fill a region with a characteristic size of the order of the scale height $H_x \approx 4 \times 10^{10}$ cm $\sim$ 0.2 $R_{\rm B8}$ (see eq. [2] and Table 2).

The hot spot produced on the following side of the B8 star by Roche lobe overflow would be best seen at phase 0.88 and would probably be eclipsed at phase 0.38. An X-ray eclipse, lagging slightly behind the primary optical eclipse, is also likely from the K star.

b) *Stellar Wind Model*

The existence of a deep surface convection zone in the K subgiant component and the proximity of the surface of the Roche lobe to the photosphere suggest that a stellar wind may exist in Algol. The nature of the flow will depend critically on the wind velocity v_w. In late-type stars it is usually low; e.g., in the Sun at 10 $R_\odot$, v_w is only 130 km s^{-1} (Allen 1973). The flow pattern of a slow wind in a double star is difficult to predict. If, as is likely, the velocity is less than $(2\,GM/R)^{1/2} \sim 700$ km s^{-1}, then the accretion radius $R_a = 2\,GM/v^2$ of the B8 star exceeds the stellar radius. In this case the B8 star will capture at least 1% of the mass lost in the stellar wind. Thus, a mass loss $\dot{M}_w \leqslant 10^{-8}\ M_\odot$ yr^{-1} is necessary to power the X-ray source at a rate $\sim 10^{31}$ ergs s^{-1}.

The velocity of the wind is probably less than the orbital velocity of 250 km s^{-1}, so $\dot{M} \approx 10^{-9}\ M_\odot$ yr^{-1} and the shock front will be spread over most of the B8 star. The ram pressure will be ~ 1 dyne cm^{-2} and the shock will form well above the photosphere (see eq. [5]). The X-ray source should be visible at all phases, with a somewhat reduced flux when the primary is eclipsed by the K star. The simultaneous existence of a wind from the B8 star would complicate matters further; it would probably have the effect of moving the shock front out to the region between the stars, and increasing the postshock temperature. If the wind velocity were much greater than the orbital velocity, then the efficiency of accretion would decrease and a higher rate of mass loss would be required. For example, $v_w \approx 600$ km s^{-1} would require $\dot{M} \approx 10^{-8}$ $M_\odot$ yr^{-1}, in which case most of the soft X-rays would be absorbed by the wind.

The temperature is likely to vary substantially in different regions, since the relative velocity at impact will depend on the angle between the velocity of the stream and that of the star. On the average, one would expect the velocity to be on the order of the free-fall velocity, corresponding to a temperature

$$T_w \approx 6 \times 10^6\ {\rm K} . \qquad (6)$$

c) *Causes of Variability*

In estimating the position of the standoff shock (see eq. [5]), we have neglected the influence of the magnetic field. If the atmosphere of the B8 star has a magnetic field ~ 100 gauss, then the magnetic pressure would be of the same order as the photospheric gas pressure; in the case of a stellar wind, it would be the dominant factor in determining where the shock would form. Observations of the Sun show that the magnetic field in the solar atmosphere is highly nonuniform; regions with field strengths ranging from less than 1 gauss to greater than a thousand gauss are present. The interaction of the streaming matter with these nonuniformities in the magnetic field could well give rise to nonuniformities in the X-ray emission. The interaction of the streams with regions of high magnetic field could also trigger stellar flares. This appears to be the most reasonable explanation for the observed radio flares. (See Woodsworth and Hughes 1976 and references therein.) The observation of a radio flare near phase 0.5 (Clark, Kellermann, and Shaffer 1975) would appear to favor a slow stellar wind model, since in the other models the interaction of the stream with magnetic field would take place in the side facing the K star and should show some sign of an eclipse.

A variation in the mass-transfer rate will also lead to a variation in the X-ray luminosity (see eq. [4]) and to a variation in the location of the shock front (see eq. [5]). The results given in Table 1 imply a factor 10 or more increase in $\dot{M}$, depending on the assumed temperature. In the Roche lobe case, this implies that the shock front is formed deeper in the photosphere, so that appreciable soft X-ray absorption should occur. A stellar wind model would produce a similar effect: increasing absorption of soft X-rays correlated with increasing X-ray luminosity until absorption becomes so strong that keV X-rays are absorbed and the source is shut off. These arguments indicate that an integrated X-ray luminosity of $\sim 10^{33}$ ergs s^{-1} is the maximum that can be expected from Algol-type systems. The SAS-3 observations apparently caught the source near its maximum.

V. CONCLUSIONS

The properties of the models discussed above are given in Table 3. The discussion of the observations and the theoretical models can be summarized as follows:

1. Algol is a soft X-ray source with $L_x \approx 10^{31}$ ergs s^{-1}. It is probably variable in the range $L_x \approx 10^{31}$–10^{33} ergs s^{-1}.

TABLE 3

PROPERTIES OF THE MODELS FOR THE ALGOL SYSTEM

Model	$\dot{M}$ (10^{-10} $M_\odot$ yr^{-1})	T (10^6 K)	Localized Source?	Prediction
Roche lobe overflow.........	1	3	Yes	Sharp eclipse
Slow stellar wind............	100	6	No	No eclipse
Fast stellar wind............	100	6	Yes	Smooth eclipse

2. The observed X-ray fluxes are consistent with a close binary mass-exchange model with $\dot{M} \approx 10^{-10}$ $M_\odot$ yr^{-1}, without either an accretion disk or a compact object. Furthermore, the mass is accreted by the *more* massive member of the system, in contrast to the usual X-ray binary models in which the accretion is onto the *less* massive, compact object. X-ray eclipses are, therefore, expected to occur roughly 180° out of phase as compared with models in which the X-rays are produced at the secondary.

3. An increase in the mass-exchange rate would result in an increase in luminosity accompanied by an increase in soft X-ray absorption, until the source is completely shut off by absorption at a mass-exchange rate of a few times 10^{-8} $M_\odot$ yr^{-1}, corresponding to a total X-ray luminosity of $\sim 10^{33}$ ergs s^{-1}.

4. The radio flares could be caused by the interaction of the streaming matter with regions of strong magnetic field on the B8 star.

An accurate determination of the temperature and of the variation of X-ray flux with phase will be possible as soon as instruments as sensitive as the present one become available for satellite observations. Such observations should be able to rule out one or more of the models proposed here.

This work was partially supported by NASA contract NAS5-23322. The authors wish to thank the following people for their competent engineering support of the rocket flight: R. Rasche, of Measurement Laboratories, Inc.; A. DeCaprio and J. Davis, of American Science and Engineering; G. Foster, of the Smithsonian Astrophysical Observatory; and the personnel of the Sounding Rocket Branch of the Goddard Space Flight Center.

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