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X-Ray Spectroscopy of Late-Type Stars

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National Aeronautics and
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X-RAY SPECTROSCOPY OF LATE-TYPE STARS

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INTRODUCTION

Over the past two years, in particular since the launch of the Einstein Observatory, it has become apparent that stars emit soft X-rays over a wide range of luminosities (up to 10^{32} ergs s^{-1}). It is generally assumed that this emission is coronal; however there has been much debate as to its precise nature and how these results relate to our current understanding of the solar corona (e.g. Linsky 1980; Walter et al. 1980; Mewe 1979; Vaiana and Rosner 1978). The Solid State Spectrometer (SSS) on the Einstein Observatory afforded the opportunity to obtain high resolution spectra of a number of these stars. The stars bright enough to give good spectra were Algol and Capella, known for several years to be X-ray sources (Schnopper et al. 1976; Catura et al. 1975) and AR Lac, HR1099, RS CVn, UX Ari and λ And among the RS CVn binaries, which were found to be X-ray sources by the low energy dedectors of the HEAO A2 experiment (Walter, Charles and Bowyer 1978a;1978b). The SSS was also used by Agrawal and Riegler (1980) to observe σ Cor B, which they had previously studied with HEAO A2 (Agrawal, Riegler and Garmire 1980), Newell and Gibson for simultaneous X-ray and radio observations of HR1099 (Newell et al. 1979) and Cruddace and Dupree to look at the W UMa representatives VW Cep and 44 Boo. We will concentrate on a discussion of the SSS observations of the RS CVn systems and Algol. Preliminary accounts of this work were given by White (1979) and Swank (1979), but because of calibration problems we were restricted to the 0.8-3.0 keV energy band. In the intervening time we have resolved these difficulties and now can use the full range of 0.5-4.5 keV. This has enormously improved the effectiveness of the SSS and made some modifications to the early results.

The SSS gives 128 channels of PHA information with a constant energy resolution of about 160 eV. (See Joyce et al. 1978, for a full description of the instrument.) To give some idea of the results we expect with the SSS, in Figure 1 we have folded the Raymond and Smith (RS) models (1977,1979) which predict the line and continuum emission from an isothermal plasma through the detector response function. Five different temperatures are shown: 5,10, 20,40 and 80 million degrees. The principal line energies are indicated and it can be seen how they are broadened by the detector response. Note how the line emission is most noticeable for temperatures below 20 million degrees.

SPECTRAL RESULTS

We attempted to fit RS models to each source. The results are given in Table 1. It is clear that a single temperature is inconsistent with the data. However a two temperature RS model gives much better χ^2 with typically about 70 for 58 degrees of freedom and temperatures of 7 and 40 million degrees. The spectra tended to fall into two categories, those with obvious line emission (in particular from Si) and those without. Figure 2 gives an example of the first category. This is from a new SSS observation of Capella that we made in September 1979. The results of this are similar to those reported in Holt et al. (1979). The contribution of the high temperature component is indicated. Also shown is the best fit model with the Fe abundance set to zero and it is clear that below 1.5 keV Fe dominates the spectrum. A similar spectrum is that of σ Cor B (Agrawal and Riegler 1980). In both cases the low temperature component dominates the spectrum, but for the rest this is not the case. Figure 3 shows spectra of AR Lac and UX Ari. Note the absence of obvious line emission from Si. The individual contributions of each component are given and it is evident that in these cases the high temperature 50 million degree continuum is dominating the spectrum above 1.5 keV. From Figure 1 we can see that little obvious line emission would be expected, primarily because Si and S are fully ionized for such high temperatures. Very similar spectra were observed for Algol (White et al. 1980).

Figure 4 quantifies these results in terms of the luminosity in the 0.4-4.0 keV band for each of the two components. For Capella, AR Lac, RS CVn, UX Ari and Algol we have had sufficient observations to see variability, so we have plotted several different values for them. Two things stand out from Figure 4. Firstly, note that while the luminosity distribution of the low temperature covers less than one decade, the distribution of the high temperature luminosity ranges over almost three orders of magnitude. Secondly, for UX Ari and AR Lac the variability is principally from the high temperature component, while for Capella the opposite is the case. The two component luminosities for 2 observations of Algol were in the same range. Both components varied. In Figure 5 we give the values obtained for the emission measure (EM) as a function of temperature. The points around 7 million degrees cluster together in temperature as well as emission measure. For the high temperature the range of emission measures is large. The range of temperatures is probably larger than for the low temperature, although the errors are large for determining kT near the cutoff energy of the telescope. Capella showed the only clear variation in the low temperature emission measure.

In order to test the uniqueness of a two temperature model and to gain some insight into the underlying temperature distribution for each source we inserted a third component at an intermediate temperature. For none of the sources did this improve the χ^2 significantly. By increasing the emission measure of the third component until the χ^2 increased by 2.7, we obtained the 90% confidence upper limits given in Table 2 for the ratio of the third emission measure to that of the weaker of the other two components. In all cases the third component is less than the other two. Thus to first order the temperature distribution is bimodal, as opposed to a single broad distribution.

During the fitting procedure the elemental abundances of Mg, Si, S and Fe were allowed to be free parameters and the resulting abundances measurements are given in Table 3. They are all within a factor 2 of solar values. Optical measurements of RS CVn, RW UMa and AR Lac (Naftilan 1975; Naftilan and Drake 1977) have suggested that the cooler star in these systems is metal poor (about 0.1 of solar). This was supported by a HEAO A2 X-ray measurement of the spectrum of UX Ari which gave an upper limit to the Fe abundance of <0.03 solar (Walter, Charles and Bowyer 1978a). But this disagrees with our result given in Table 3 and examination of Figure 3 clearly shows a bump at $\sim$ 1 keV that comes primarily from $\mathrm{Fe}_{\mathrm{XX}}$. The discrepancy between the X-ray measurements may be accounted for by the fact that any abundance measurements depend on the assumed model. In the preliminary analysis of our data that we reported at the I. A. U. meetings we only used the 0.8-3.0 keV band.For this more limited energy range we only require one temperature, but with an Fe abundance of 0.1 solar. It is only when we use the full energy range of the SSS that the need for a two temperature spectrum becomes apparent and the Fe abundance approaches solar values. We note that Walter, Charles and Bowyer only used a single temperature model and this, along with less good energy resolution of the proportional counters, presumably accounts for the discrepancy.

While our data allows and in many cases establishes the presence of the heavy elements Si, S and Fe, the errors given on the abundances are within the context of a two temperature model and the atomic physics used in the RS models. Although they are not very sensitive to the inclusion of additional components, it is possible that with a more complex distribution the abundances in most cases could be solar. Possible mechanisms for affecting the apparent abundances in Capella are discussed in Holt et al. (1979). In several cases it is possible to fit the data with a low temperature collisional equilibrium spectrum with solar abundances and a power law component, if the latter is absorbed by a column density of cold material as large as $5\mathrm{x}10^{21}\mathrm{cm}^{-2}$. For Algol however, the fit is always significantly worse than the fit for two thermal components. The emission measures do depend on the abundances, especially for the low temperature component, since the contribution of the lines is large. (See Figures 2 and 3.) In most cases errors on EM in Figure 5 cover the difference between the values for the best fit abundances and the values if the abundances are set equal to solar.

VARIABILITY

Capella, AR Lac, RS CVn, UX Ari and Algol showed fluxes different by factors of $\sim$2 in our observations. Our observations were not continuous, however, and for the RS CVn stars we did not catch the transitions between intensity levels, which were nearly constant for hours at a time. Are these flux variations the result of flares, similar to that reported by White, Sanford and Weiler (1978) or are they related to the photometric wave as suggested by Walter et al. (1980)? In the latter case we would expect to see X-ray flux in anti-phase with the photometric wave. For RS CVn the maximum flux was near wave minimum at phase 0.0 and Walter et al. (1980) found that UX Ari was not detectable near photometric wave phase 0.5. On the other hand fluxes different by 50% have been observed from UX Ari at wave minimum and the maximum X-ray flux observed was at phase 0.25 (Swank et al. 1980).

Modulation with photometric phase is only expected if the X-ray emission region is confined close to the surface of the cool star and to the "spotted" region. The eclipsing system AR Lac allows the structure of the corona to be investigated. Figure 6 shows our observation during eclipses of the K0 and G5 stars. The small diagrams illustrate the relative sizes of the two stars and how each eclipse progressed. The shading represents a very idealized view of the star spot activity on the cool star extrapolated from the wave minimum given by Chambliss, Hall and Richardson (1976). We note the following: (1) There is no evidence for any significant variations in the X-ray flux through each eclipse, in particular as the proposed active side of the K star is occulted. (2) The count rate during the secondary eclipse is 60% of that in the primary eclipse.

Because the K star is bigger than its companion, only a very shallow X-ray eclipse would be expected, so the fact that no sharp X-ray eclipse is seen during the secondary eclipse is not very surprising. The question is: how much results from the partial eclipse of the corona surrounding the K star? Most of the flux variation was in the high temperature component (Figure 4) for AR Lac as for UX Ari. As discussed below, this suggests that the change is intrinsic. Observations are needed through several orbital cycles to look for repeatable features in the light curve. In this way it should be possible to deconvolve the real eclipse from variations caused by the observations of active regions on one side of the star or by flaring activity.

Figure 7 shows the flux recorded during two observations of Algol. Also given is the binary phase of the 2.9 day period of Algol A and B, where phase zero corresponds to the primary optical minimum. The optical eclipse lasts from phase 0.9 to 0.04 and we see no evidence for the corresponding X-ray minimum that might be expected from mass transfer models for the X-ray emission (Harnden et al. 1976). In fact during the second observation there is an X-ray flare that peaks in the middle of the optical eclipse and then decays over the following 12 hours, a time scale similar to that of the radio flares (Hjellming, Webster and Balick 1972). For Algol there is thus clear evidence for intrinsic variability.

DISCUSSION

The X-ray spectra of the sample of stellar systems we have discussed here all indicate two components. The lower energy components in all of them are consistent with emission due to gas of 3-7 million degrees in collisional equilibrium as calculated by Raymond and Smith (1977,1979). In all cases the abundance of Fe in this component exceeds 0.1 solar at the 90% confidence level and could be within a factor of 2 of solar. The high energy components can be due to gas in collisional equilibrium at 15-100 million degrees, although some are a little low in the emission lines of hydrogenic Si and S. A power law alternative does not appear likely, however, in that the high column density attending such fits would indicate emission from near the photosphere which would be subject to distinct eclipse, or modulation with photometric phase in the case of the RS CVn stars, neither of which has been observed. Of course an isothermal equilibrium gas is most probably too simple a model for this, if not both, components, but it appears to be a reasonable first approximation.

Each of the sample is a binary which is thought to contain a late-type subgiant. The "starspot" model of the photometric wave phenomenon of the RS CVn systems (Hall 1972,1978) suggests magnetically confined hot plasma in analogy with the sun. Algol is different from the RS CVns in that the subgiant (Algol B) is filling its Roche lobe. Harnden et al. (1977) discussed possible production of X-rays in shocks of material transferred to Algol A either in a stream through the Lagrangian point or from a stellar wind. However the free fall velocities are less than 700 km s^{-1} and the temperatures expected are less than about 7 million degrees, so that this mechanism does not seem a promising explanation, at least of the high temperature. As we have pointed out, our spectra of Algol are very similar to those of the RS CVn systems. Thus the similarity in radio properties of Algol and UX Ari (Gibson, Hjellming and Owen 1975) is paralleled by similarity in X-ray properties. Despite some differences, the emission scenarios seem likely to be very similar and more related to the nature of the subgiant than to the existence of mass exchange, although that may indeed occur.

The luminosities of the low temperature components are distributed about $3x10^{30}$ergs s^{-1} with a dispersion of about 40%, the luminosities of the high temperature components about $6x10^{30}$ergs s^{-1} with a dispersion of near 100%. The Einstein IPC observations reported by Vaiana (1980) and others on stars of all spectral types have indicated that the components of these binary systems could be expected to be sources of 10^{27}-10^{30}ergs s^{-1}. The lower luminosities of the RS CVn binaries we have observed are about equal to the higher luminosities for stars of their type and the mechanisms could be the same, perhaps enhanced by more extreme parameters induced by their binary situation. As Charles (1980) reports, the Einstin IPC observations suggest a bimodal luminosity distribution for RS CVn systems. It will be interesting to see if the lower luminosity systems perhaps lack the high temperature component we see in the brightest.

There seems in Figure 5 to be less dispersion in the emission measures for the low temperature component than the high temperature component. Since the radii of the subgiants in our sample are similar, if we assume the subgiant is the X-ray source, this reflects similar surface fluxes. Table 4 shows estimates of the radii of the subgiants thought the likeliest candidates for the strongest sources in the systems and luminosities per area of these candidates, for both the low and high temperature components. For both components these values are lowest for λ And and Capella, which have the longest rotation periods and smallest tangental velocities. However, other variables must influence the results as well. The same can be said of the luminosity per volume of a shell around the subgiants of thickness of the order of the radius. Simon and Linsky (1980) suggested that flares could involve magnetic flux reconnections between binary components and that this would be more prevalent and strong in closer binaries. In λ And and Capella the companions indeed subtend the smallest solid angles, but that for UX Ari is also small. A combination of variables is difficult to study with our limited sample.

Several crude estimates of the dimensions of the emission regions can be made assuming thermal emission.

First, if approximate hydrostatic equilibrium is assumed, as by Ayres and Linsky (1980) for Capella, for the ratio of the pressure scale height to the stellar radius,

$$\frac{h}{R} = .7\ T_7\ R\ M^{-1},$$

where R and M are in solar units and T_7 is the temperature in 10^7°K. For the temperatures of both components h/R is on the order of or greater than one, so that the gravitational field of the star is not controlling the extent of the gas.

Walter et al. (1980) have applied the model of Rosner, Tucker and Vaiana (1978) to estimate the dimensions of loops of plasma. For a constant loop pressure p the loops would extend a distance L above the surface,where

$$\frac{L}{R} = 5\ T_7^3\ R^{-1} p^{-1}.$$

Pressures at the base of the transition region on the order of 0.1-10 dynes cm^{-2} have been deduced for Capella, λ And and UX Ari (discussed in recent papers be Baliunas and Dupree 1979, Ayres and Linsky 1980 and Simon and Linsky 1980). For the low temperature components it is possible for such pressures to have loops less than the stellar radii and scale heights. However for the high temperature components the loops would extend to the binary companions, even for Capella.

A third measure of the size is provided by the emission measure. For a volume extending a height ℓ above the surface over a solid angle 2πf,

$$\frac{\ell}{R} + \left(\frac{\ell}{R}\right)^2 + \frac{1}{3}\left(\frac{\ell}{R}\right)^3 = 360\ EM_{53}\ T_7^2 p^{-2} R^{-3} f^{-1}.$$

Like the loop lengths the values of ℓ (for f=1) are almost all on the order of the stellar radii or larger unless the pressures exceed 1 dyne cm^{-2} and for the high temperature components even if the pressures approach 10 dynes cm^{-2}. The exception is Capella for which ℓ (p=1) is only .2 of the stellar radius for the low temperature component. The high temperature components almost always require ℓ several times as large as do the low temperature components (for given f and p). Table 4 shows for the low temperature component ℓ/R and for the high, ℓ/a for f=1 and p=1. The hot components reduce to stellar size for pressures of 1-10 dynes cm^{-2} for λ And and Capella, 10-100 dynes cm^{-2} for the rest. These results, along with the independent variability of the soft and hard components in Capella, UX Ari and AR Lac (but not Algol perhaps) suggest that if there are magnetic loop structures, they are of two kinds, one at ~7 million degrees of approximately stellar size, the second at ~40 million degrees and larger (in most cases as large as the binary system) and/or of higher pressure. Pressures of 100 dynes cm^{-2} are characteristic of some types of solar flares (Pallavicini, Serio and Vaiana 1977).

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All of these measures (which can only be rough estimates in the indicated regimes) are consistent with the high temperature component being emitted in a large volume which would not be significantly eclipsed. This would suggest a flare interpretation of the variability seen. In this picture the high temperature component would arise in the same region as the radio emission in those sources known to be active in the radio (Owen and Spangler 1977; Feldman et al. 1978). This would seem to confirm the suggestion by Simon and Linsky (1980) that strong magnetic fields (~ 100 g) with dimensions of the binary system are involved in heating the plasma, although it could be more compact, if at high pressure. (The time scale of the Algol flare does imply $\gtrsim 10$ dynes cm^{-2}, if due to radiative cooling.) The low temperature component would be more confined and would therefore be more likely to be eclipsed or modulated if associated with a "starspot" area. Is it only coincidental that all of these systems can be reconciled with neither more nor less than two temperature components, with dimensions which are consistent with the stellar and orbit dimensions, respectively? Future observations should attempt to separate the phase dependences and flare time scales of soft and hard components.

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Table 1. One and Two Temperature Fits

Source	T*	χ^2 (60dof)	T^*_1	T^*_2	χ^2 (58 dof)
σ Cor B	7	250	6	50	76
AR Lac	8	200	7	50	76
HR1099	20	500	8	50	61
Algol	12	180	7.5	40	80
RS CVn	14	102	6	50	67
UX Ari	12	219	8	50	73
λ And	6.5	112	7	50	65
Capella	5	210	4.5	13	90

*Temperatures in units of 10^6 °K.

Table 2. Three Component Model

Source	EM_3/EM_2	EM_3/EM_1
σ Cor B		< 0.9
AR Lac	< 0.7	
HR1099	< 0.6	
Algol	< 0.3	
UX Ari	< 0.4	
λ And	< 0.4	
Capella		< 0.9

Table 3. Abundances* in Two Temperature Models

Source	Si	S	Fe
σ Cor B	0.9 ± 0.2	< 1.5	$0.9^{+0.4}_{-0.1}$
AR Lac	< 1.2	< 3.0	$0.7^{+0.4}_{-0.1}$
HR1099	$0.4^{+0.4}_{-0.2}$	$0.6^{+0.7}_{-0.4}$	0.4 ± 0.3
Algol	1.5 ± 1.1	< 1.5	1.4 ± 0.5
UX Ari	$0.3^{+0.3}_{-0.2}$	< 1.0	$0.5^{+0.1}_{-0.05}$
λ And	0.6 ± 0.5	1.6 ± 1.0	0.5 ± 0.5
Capella	2.7 ± 0.7	< 3.0	2.1 ± 0.2

*Abundances relative to solar (log N = 12, 7.57, 7.20, 7.51 for H, Si, S, Fe, respectively). Errors are 90% confidence.

Table 4. Parameters of Most Active Star

Source	P(d)	R($R_\odot$)	a($R_\odot$)	v_t	f_1	ℓ_1/R	f_2	ℓ_2/a	Ref.
σ Cor B	1.14	2	6	89	1.4	3.5	.26	4	1,2
AR Lac	2.0	3.1	9	79	.76	2.6	.50,1.2	4 , 7	3,4
Algol	2.87	3.4	14	60	.15,.30	1.3,1.6	.29,.48	2 , 3	5
RS CVn	4.8	4	17	42	.40	1.6	.90	5	3
UX Ari	6.4	3	20	24	1.1	3.0	2.7,1.6,3.6	3, 3, 6	6,2
λ And	20.5(50)	6.2	45	6	.11	.80	.07	5	7,2
Capella	104(12)	7.1	160	30	.05,.10	.15,.21	.006	.01,.05	8

Col.2: Values in parentheses are rotation periods.
Col.3: Estimated or measured radius.
Col.5: tangental velocity (km s^{-1}).
Col.6 and 8: $[f_i] = 10^7$ ergs $s^{-1}cm^{-2}$ in the range 0.4-4.0 keV. i=1,2 for low and high temperature.
Col.7 and 9: ℓ_i = extent above surface of emission region.
Ref. (for system parameters): (1) Tanner(1949); (2) Young and Koniges(1977); (3) Hall(1976); (4) Popper and Ulrich(1977); (5) Harnden et al.(1977); (6) Simon and Linsky(1980); (7) Gratton(1950); (8) Ayres and Linsky(1980).

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FIGURE CAPTIONS

Figure 1 - Reponse of the Solid State Spectrometer to the spectra of isothermal plasmas in collisional equilibrium. The ions contributing strong lines are indicated at the line energies.

Figure 2 - Pulse height spectrum of Capella. The histogram shows the response to the best fit model. Dashed curves show the contributions of everything but Fe and of the high temperature component alone.

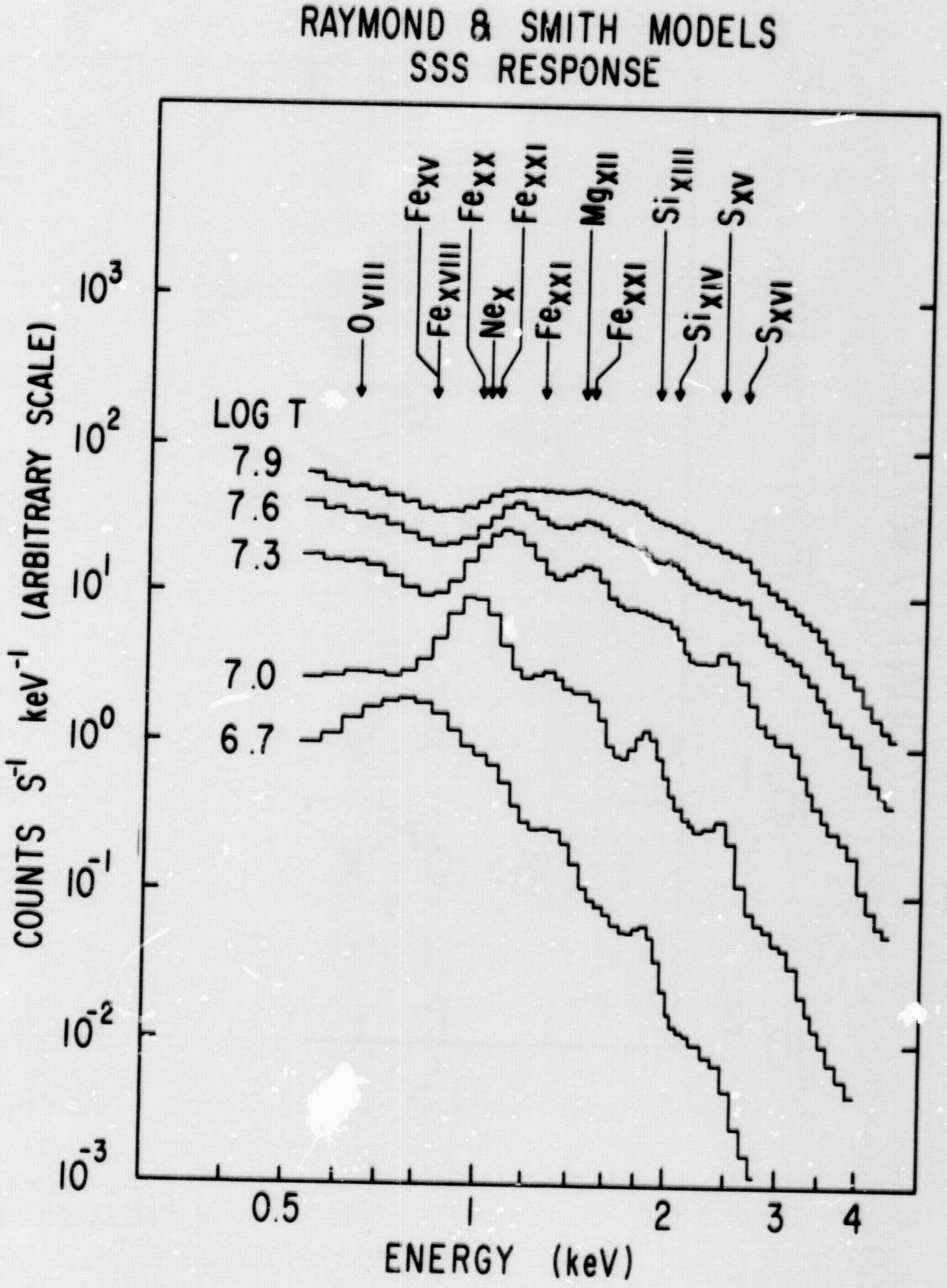
Figure 3 - a. Pulse height spectrum of AR Lac. Dashed curves are the contributions of the low temperature component with Fe (a) and without Fe (b) and the high temperature component (c).
b. Pulse height spectrum of UX Ari. Dashed curves show contributions of low and high temperatures. Best fit abundance of Fe of 0.5 solar was used in the models.

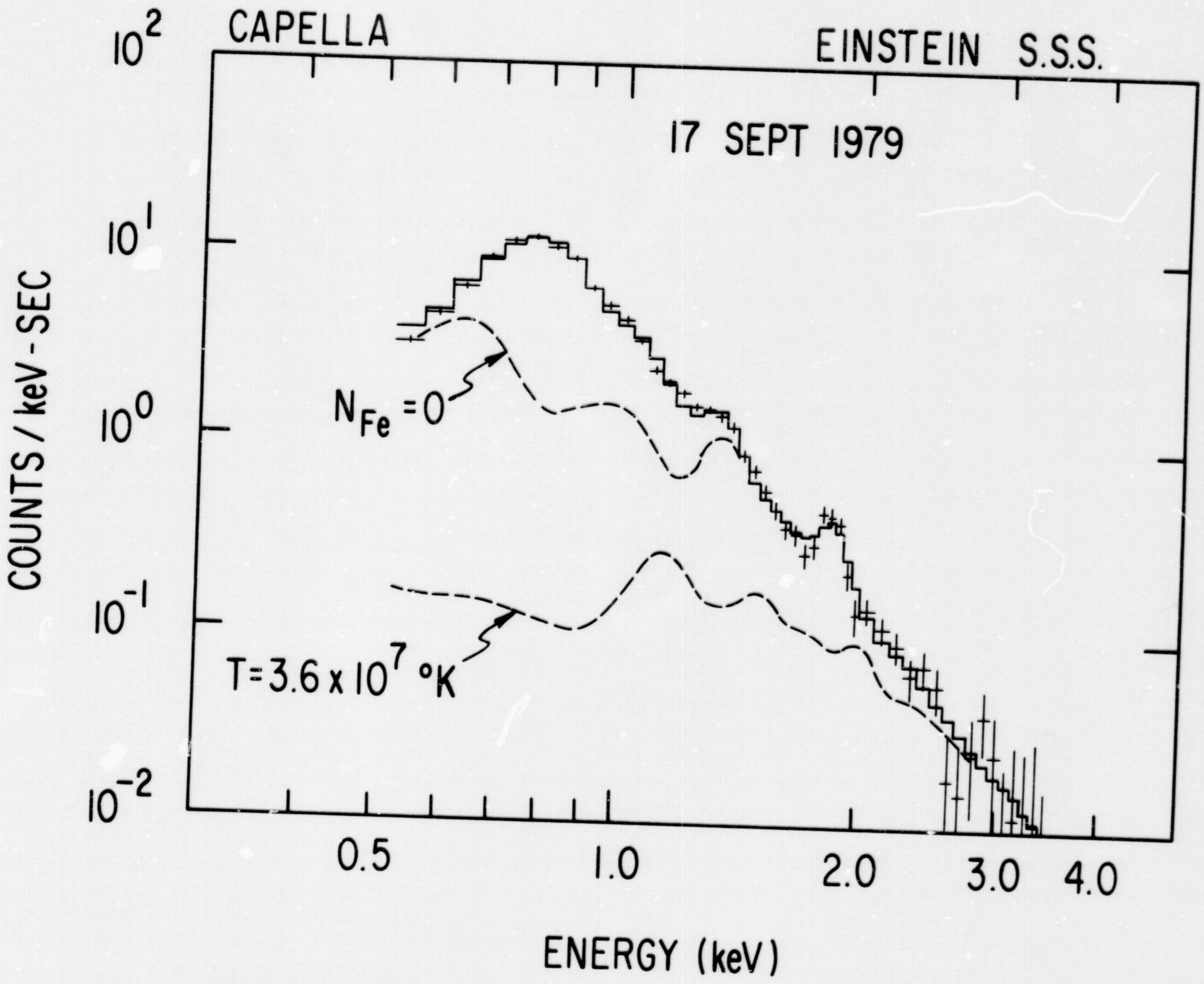
Figure 4 - Luminosity (0.4-4.0 keV) of high temperature component versus luminosity of low temperature component. Values for Algol as well as for the RS CVn systems are plotted.

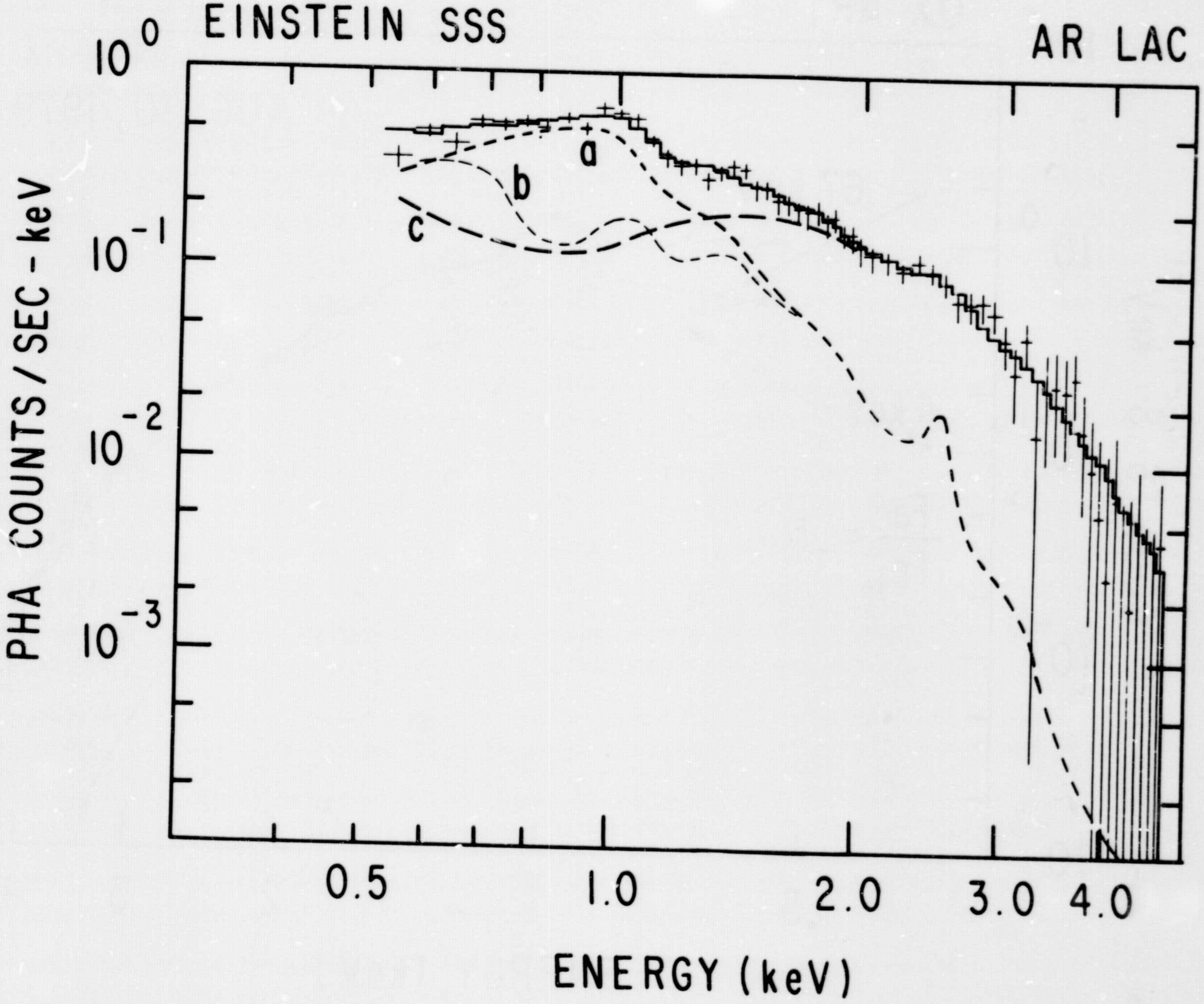
Figure 5 - Emission measure (EM) versus temperature T for both components. All points to the left of log T = 7 are for the low temperature components. Multiple points for a given source are from different observations.

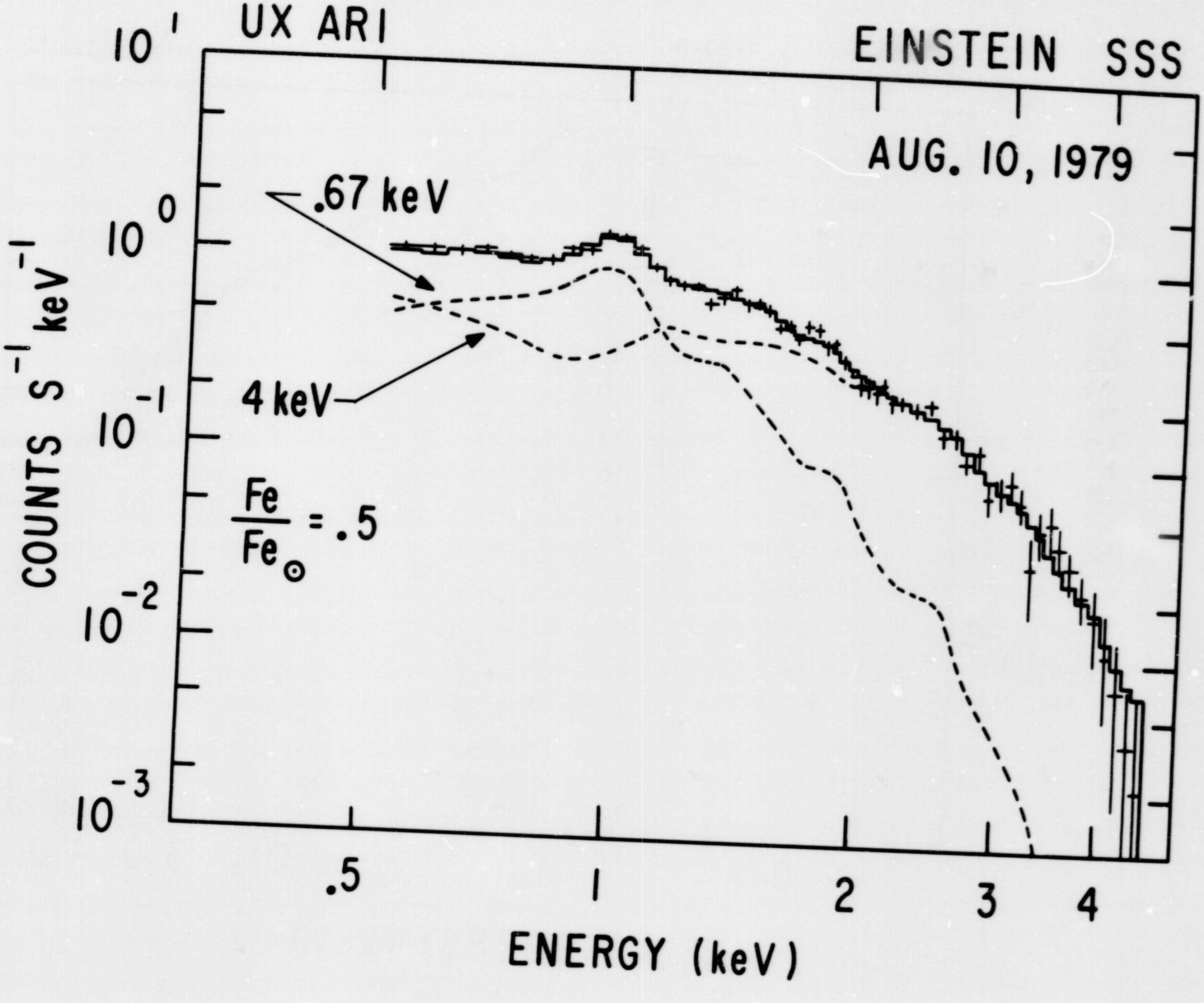
Figure 6 - Count rates observed for AR Lac during optical primary and secondary eclipses. The diagrams indicate our view of the binary during the observations. The small circle represents the G5 star and the large circle the K0 subgiant with the dark half indicating the "spotted" hemisphere.

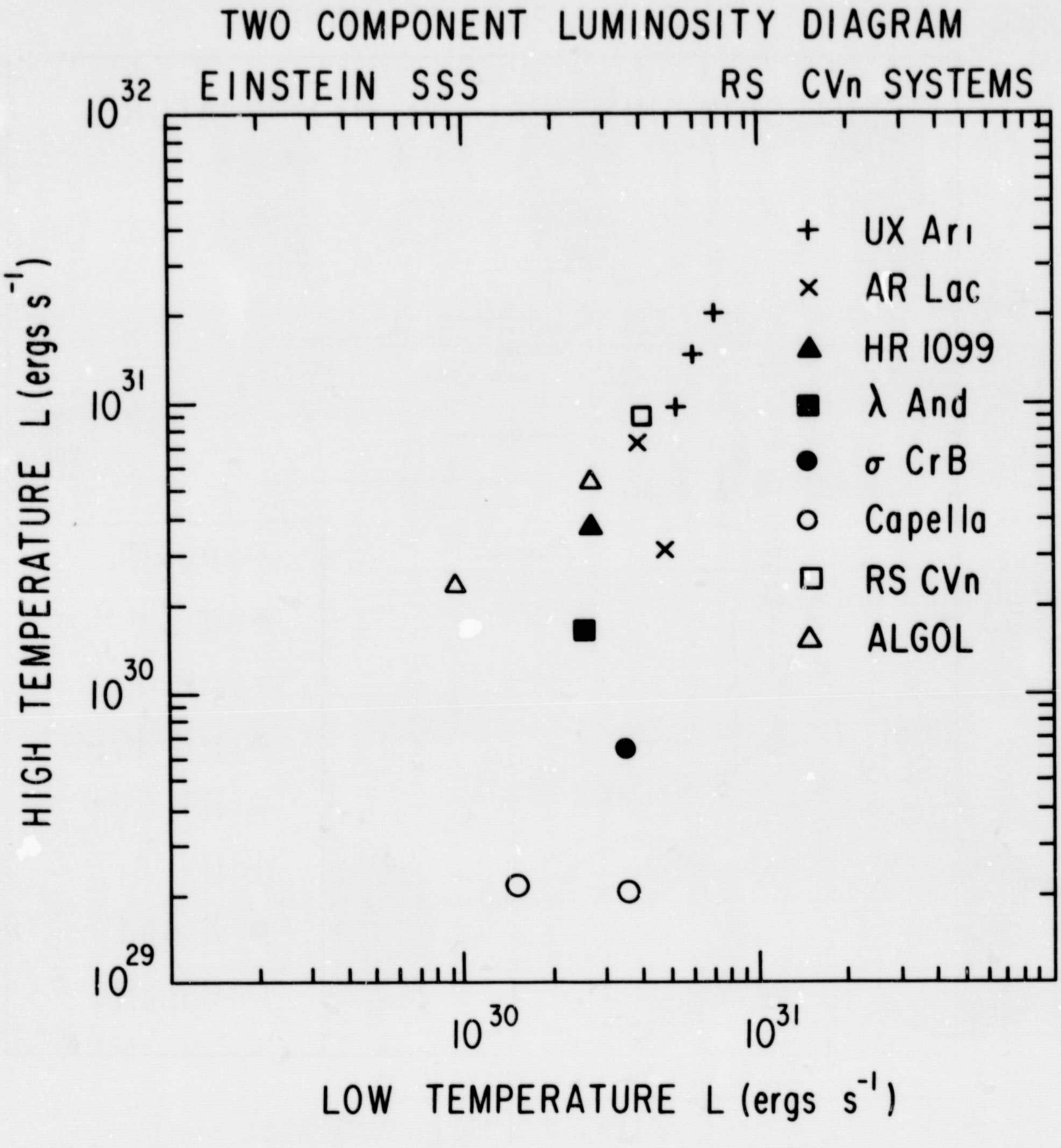
Figure 7 - Count rates observed during observations of Algol 6 mo. apart. Due to changes in the experiment the maximum count rate in August corresponds to about three times the flux in February. Binary phase zero is optical primary eclipse.


RAYMOND & SMITH MODELS
SSS RESPONSE
COUNTS S^{-1} keV^{-1} (ARBITRARY SCALE)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
ENERGY (keV)
0.5
1
2
3
4
LOG T
7.9
7.6
7.3
7.0
6.7
O$_{VIII}$
Fe$_{XV}$
Fe$_{XVIII}$
Fe$_{XX}$
Ne$_{X}$
Fe$_{XXI}$
Fe$_{XXI}$
Mg$_{XII}$
Fe$_{XXI}$
Si$_{XIII}$
Si$_{XIV}$
S$_{XV}$
S$_{XVI}$


CAPELLA
EINSTEIN S.S.S.
17 SEPT 1979
$N_{Fe} = 0$
$T = 3.6 \times 10^7$ °K
COUNTS / keV - SEC
10^2
10^1
10^0
10^{-1}
10^{-2}
0.5
1.0
2.0
3.0
4.0
ENERGY (keV)


EINSTEIN SSS
AR LAC
PHA COUNTS / SEC - keV
10^0
10^{-1}
10^{-2}
10^{-3}
a
b
c
0.5
1.0
2.0
3.0
4.0
ENERGY (keV)

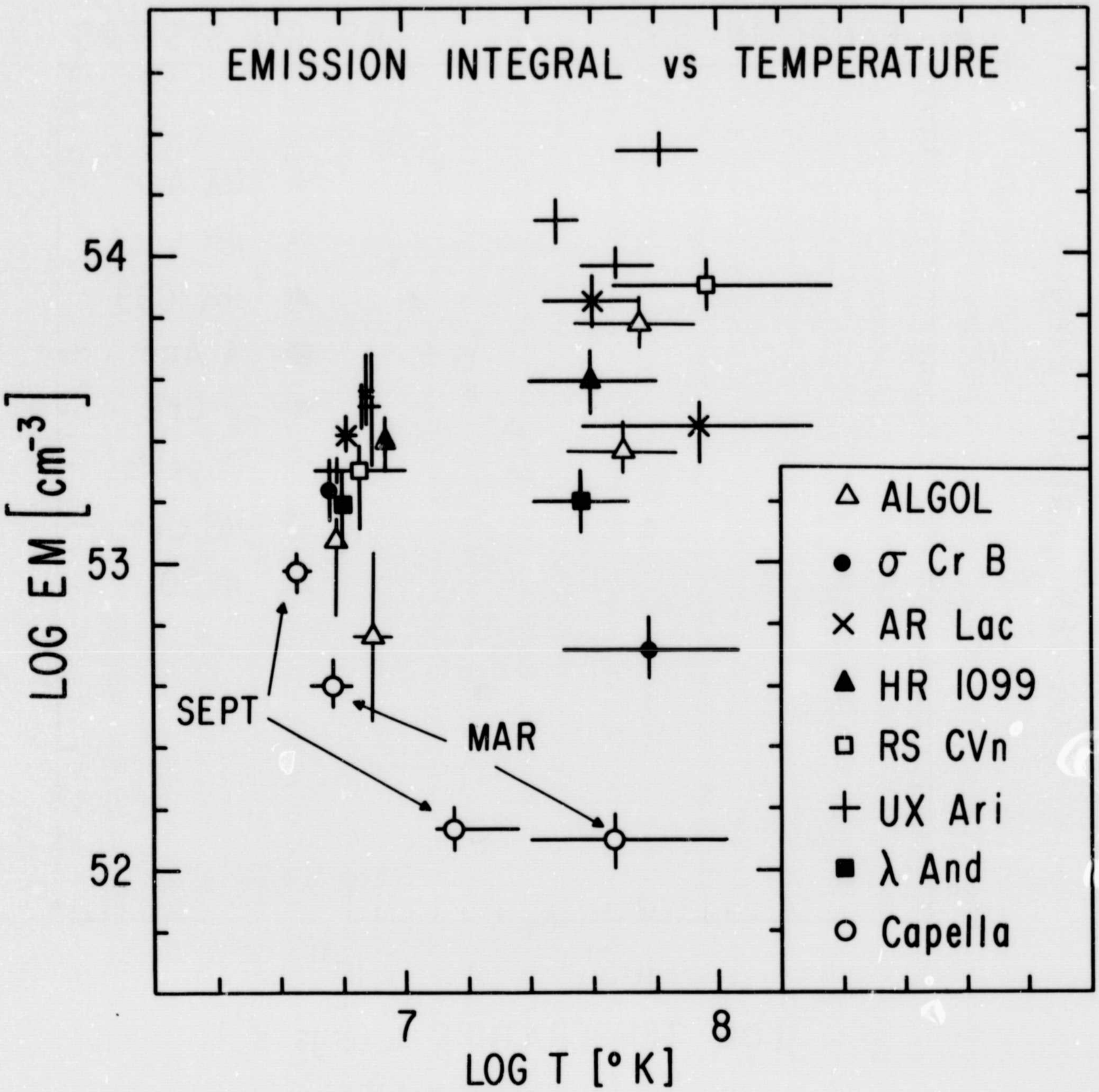

UX ARI
EINSTEIN SSS
AUG. 10, 1979
.67 keV
4 keV
$\frac{Fe}{Fe_\odot} = .5$
COUNTS S^{-1} keV^{-1}
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
ENERGY (keV)
.5
1
2
3
4

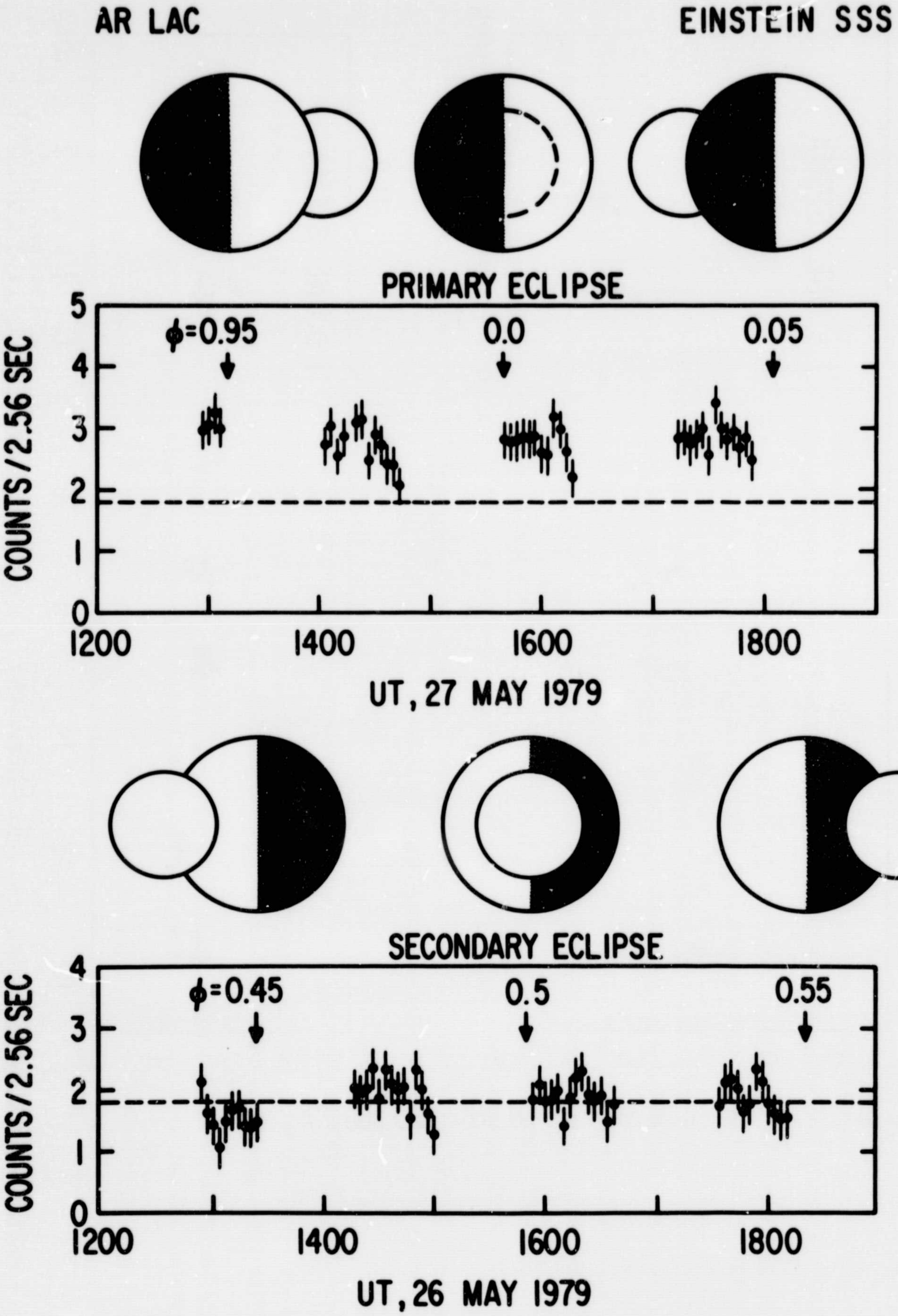


TWO COMPONENT LUMINOSITY DIAGRAM

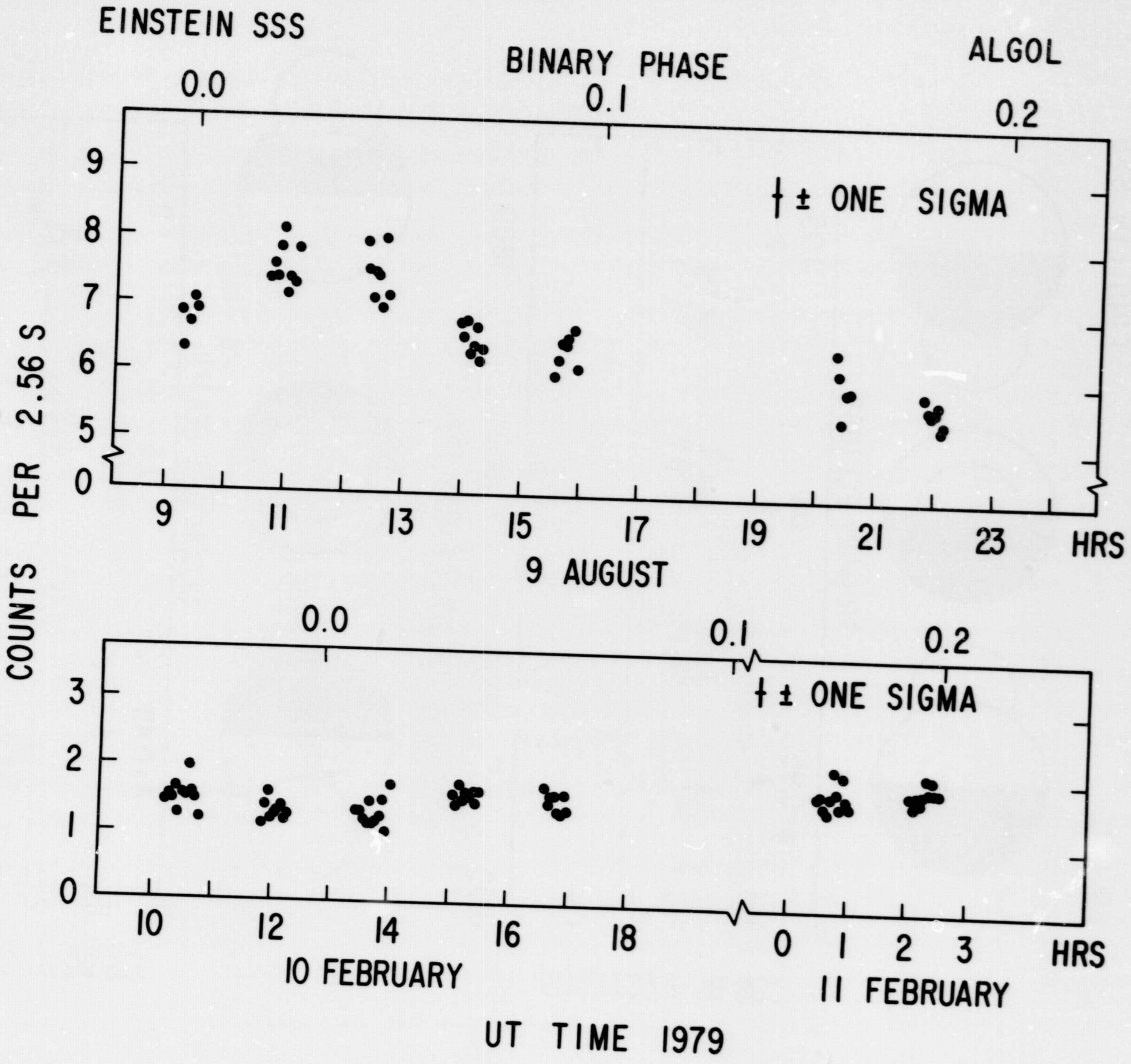
EINSTEIN SSS RS CVn SYSTEMS

TWO COMPONENT MODELS





ORIGINAL PAGE IS
OF POOR QUALITY


EINSTEIN SSS
BINARY PHASE
ALGOL
0.0
0.1
0.2
± ONE SIGMA
9
8
7
6
5
0
9
11
13
15
17
19
21
23
HRS
9 AUGUST
COUNTS PER 2.56 S
0.0
0.1
0.2
± ONE SIGMA
3
2
1
0
10
12
14
16
18
0
1
2
3
HRS
10 FEBRUARY
11 FEBRUARY
UT TIME 1979