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EINSTEIN DETECTION OF X-RAYS FROM THE ALPHA CENTAURI SYSTEM

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ABSTRACT

We report detection of quiescent X-ray emission from the stellar components of the α Cen system: α Cen A (G2 V) and α Cen B (K1 V). Contrary to previous theoretical expectations (e.g., Mewe), *both* stars are X-ray emitters and at about the same level: $L_x = 1.2 \times 10^{27}$ and 2.8×10^{27} ergs s^{-1} for A and B, respectively; the sum of these values is in agreement with the emission level previously reported for α Cen by Nugent and Garmire. Comparison with previous chromospheric and transition region measurements indicates that α Cen A and B may have changed in relative strength in recent years. The coronal temperature of the combined Cen AB source, which is dominated ($\sim \frac{2}{3}$ of the total) by the K star, is $(2.1 \pm 0.4) \times 10^6$ K, similar to that of the average solar corona; this value is not consistent with the estimate of 5×10^5 K quoted by Nugent and Garmire. The applicability of coronal loop models and the conclusions which can be drawn on the basis of such models are discussed, using the Sun and the α Cen stars as examples.

Subject headings: stars: coronae — stars: individual — X-rays: sources

I. INTRODUCTION

The nearest late-type main sequence stars are α Cen A (G2 V) and B (K1 V) and their common proper motion companion Proxima Cen (α Cen C, dM5e). This system is of special interest, not only because it is the Sun's nearest neighbor, but also because its closeness makes the three component stars the brightest available targets of their respective spectral types, thus allowing for the most sensitive and detailed measurements at all wavelengths. In the X-ray range, the system is close enough to allow detection of solar level X-ray emission in only a few seconds. In addition, the spatial resolution of the *Einstein* Observatory is sufficient to resolve the stars of this system and thus determine which star is emitting. Since we are effectively observing single stars, these observations may help to rule out the possibility that the trend toward higher surface X-ray emission in late-type dwarfs and the prevalence of X-ray emission in late-type stars in general (Vaiana *et al.* 1981) is strongly influenced by duplicity.

The system spans a full decade in stellar mass and almost 10^3 in bolometric luminosity (see Table 1). The binary pair α Cen AB is expected to have the same initial composition and the same chronological age, so that differences in coronal properties between the two are likely to reflect a general characteristic of coronal formation as a function of spectral type. As a test case for theories of coronal heating, this system by itself can be used to provide stringent constraints upon theory, particularly in the case of heating by acoustic flux (see, e.g., Rosner and Vaiana 1979).

As we shall also show in the following (§ III), the likelihood that these stars have solar-type coronae make them ideal test cases for an extension of loop modeling from the solar to the stellar case. We shall examine in detail the considerations which must go into the use of recent solar work (see, e.g., Vaiana and Rosner 1978; Serio *et al.* 1981) when attempting to determine parameters of extended stellar atmospheres from unresolved diagnostics, including the applicability of scaling laws for closed loop atmospheres (Rosner, Tucker, and Vaiana 1978; Galeev *et al.* 1981) as applied to the integrated emission from a stellar corona.

II. X-RAY OBSERVATIONS

a) Source Locations and Identification

Alpha Cen was observed twice, once with the imaging proportional counter (IPC), which has spectral capability and high sensitivity, and once with the high resolution imager (HRI), which has limited spectral resolution but

TABLE 1

PHYSICAL DATA FOR COMPONENTS OF ALPHA CENTAURI AND FOR THE SUN

Component	Sp	M_V[a]	M_{bol}[a]	T_{eff}
α Cen A	G2 V	4.38 ± 0.02	+4.3	5630[b]
α Cen B	K1 V	5.72 ± 0.02	+5.5	5040[b]
Prox Cen	dM5e	15.49 ± 0.03	+11.7	2700[c]
Sun	G2 V	4.83 ± 0.03	+4.8	5770

[a] Kamper and Wesselink 1978.
[b] Flannery and Ayres 1978.
[c] Frogel *et al.* 1972.

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[2] *Einstein* Observatory Guest Observer.
[3] Also Osservatorio Astronomico di Palermo.

very high spatial resolution. The IPC has a field of view of $\sim 1° \times 1°$, a spatial resolution of $\sim 1'$, and an effective area of $\sim 100\ cm^2$ at 1 keV. The spectral sensitivity of the instrument is nominally 0.2–4 keV, and detected photons are timed to $\sim 63\ \mu s$. The HRI has a spatial resolution of $\sim 4''$; it is equal to the IPC in sensitivity for soft sources and is less sensitive for extended and hard sources. Further details of the *Einstein* instrumentation may be found in Giacconi *et al.* (1979).

The dates, times, and durations of the observations are given in Table 2. The long IPC observation consisted of three consecutive orbits of data collection over an elapsed time of nearly 5 hr. The HRI pointing was ~ 0.5 hr during a single satellite orbit.

Alpha Cen was detected in both the IPC and the HRI observations. The IPC count rate was 1.25 counts s^{-1}, yielding over 12,000 photons during the three orbits and making this one of the stronger stellar sources observed by *Einstein*. The total X-ray luminosity is consistent with that reported by Nugent and Garmire (1978), who reported the probable identification of a point source seen by the *HEAO 1* A-2 detector as α Cen. The brief HRI observation yielded 153 counts for α Cen A and 333 counts for α Cen B; these may be compared with the threshold of 5 counts as the 3 σ upper limit on false detections due to noise sources in a 1000 s observation.

Figure 1 (Plate 6) shows the IPC image of α Cen (upper left) and the HRI image (lower right), with the two stars clearly resolved in the HRI. The K star α Cen B is visibly stronger than the solar-type α Cen A; both images are to the same scale.

The differences found between the best-fit X-ray locations of the sources and their known optical locations are consistent with the quoted spatial resolutions of the IPC and HRI. In particular, the strong constraint (better than 9″) provided by the HRI pointing leaves no doubt as to the identifications of both α Cen A and B as X-ray sources.

b) *Temporal Variability*

During three consecutive satellite orbits of observation, covering a total elapsed time of 4.5 hr, no significant variations in the total X-ray luminosity of α Cen were observed. The 3 σ upper limit for variability on a 5 minute time scale is 7%, and the limit to variability on a 90 minute time scale is 2%. Such constancy in the integrated emission from the Sun is often observed (see, e.g., Krieger *et al.* 1972), so that there is no reason from this observation to rule out the possibility of solar-type coronae on the α Cen stars.

TABLE 2

EINSTEIN OBSERVATIONS OF ALPHA CENTAURI AB AND OPTICAL IDENTIFICATIONS

Instrument	Observation Date	Duration (s)	X-Ray Position	Source
IPC	1979 Aug 26 0722–1200 UT	10,630	$14^h35^m59^s.6$ $-60^d37^m18^s$	α Cen
HRI	1979 Sep 2 0124–0152 UT	1,093	$14^h35^m56^s.6$ $-60^d37^m20^s$	α Cen A
			$14^h35^m55^s.1$ $-60^d37^m39^s$	α Cen B

c) *IPC Observations: Determination of Plasma Parameters*

The IPC energy range of 0.2 to 4 keV is determined at high energy by loss of mirror effective area due to limiting reflectivity; a similar drop occurs at low energies due to absorption losses in the entrance window. Pulse-height analysis of the proportional counter signals gives a FWHM energy resolution of $\sim 100\%$ at 1.5 keV.

We have used programming developed at the Center for Astrophysics which accounts for both statistical and instrumental uncertainties in the instrumental response and which employs the conventional technique of convolving model spectra with the instrument response. The method also includes varying the free parameters of the model and determining their best-fit values by minimizing the χ^2 values of the predicted versus the observed pulse-height data. Uncertainties in the free parameters are similarly obtained by examining the variation in χ^2 around the minimum value. The model used was the thermal plasma model of Raymond (1979, personal communication; see also Raymond and Smith 1977) with *cosmic* abundances folded through interstellar absorption, based upon the description by Brown and Gould (1970).

Because of its limited bandpass and spectral resolution, the IPC was not used to determine the plasma temperature kT and the interstellar hydrogen column density N_H independently. A precise determination of kT can be made only if an independent *a priori* constraint exists for N_H. In the case of α Cen, it appears reasonable to assume a low N_H because of the proximity of the system. For example, Dupree, Baliunas, and Shipman (1977) find $N_H \approx 8 \times 10^{17}\ cm^{-2}$ (cf., however, McClintock *et al.* 1978), and we shall adopt this value in the following. In consequence, we are able to analyze the IPC data by varying kT only. Had both the temperature and N_H been allowed to vary, equally acceptable χ^2 fits could have been obtained at substantially higher values of N_H (and correspondingly lower values of kT). The best-fit model is shown in Table 3, with joint 90% confidence intervals based upon the $\chi^2 + 2.7$ criterion of Avni (1976).

The HRI count rates listed in Table 2 have been used to infer the differences in X-ray luminosities and emission measures of the two components under the assumption of a common temperature for both stars; the results of this assumption are self-consistent. The observed IPC spectrum of α Cen and the best-fit thermal spectrum are shown in Figure 2.

It is instructive to examine the average surface flux of X-rays from α Cen A and B and to compare them with solar values. Using the total X-ray luminosity values of Table 3 and stellar radii of 1.23 and 0.87 $R_\odot$ derived from the M_{bol} and T_{eff} values of Flannery and Ayres (1978), we obtain the average surface flux values F_x listed in Table 4.

TABLE 3

ALPHA CENTAURI AB MEASURED CORONAL PARAMETERS

Source	L_x (ergs s^{-1})	T[a] ($\times 10^6$ K)	EM[a] (cm^{-5})
α Cen A	1.2×10^{27}	2.1 ± 0.4	$2.0 \pm 0.2 \times 10^{49}$
α Cen B	2.8×10^{27}	2.1 ± 0.4	$4.7 \pm 0.3 \times 10^{49}$
Sun:[b]			
Solar max	1×10^{28}	3.0	$\sim 10^{50}$
Solar min	1×10^{27}	1.8	$\sim 10^{49}$
Average	2×10^{27}	2.2	$\sim 10^{49.2}$

[a] Tabulated uncertainties are joint 90% confidence intervals based on an interstellar hydrogen column density of 8×10^{17}.

[b] Vaiana and Rosner 1978.

TABLE 4

CORONAL PARAMETERS FOR ALPHA CENTAURI SYSTEM

Star	F_x (ergs cm^{-2} s^{-1})	s_p (cm)	f_c[a]	p_c[a]
Sun	3.3×10^4	1.0×10^{10}	0.09	0.46
α Cen A	1.3×10^4	1.4×10^{10}	0.05	0.34
α Cen B	6.1×10^4	9×10^9	0.15	0.56
Prox Cen	7×10^5	7×10^9	0.19	3.8

[a] These quantities are the coronal filling factor and coronal pressure in the emitting regions, in the special case that all of the identical loops in the atmosphere are as high as the pressure scale height; see text for details.

The solar value is a typical quiet-Sun level (Vaiana and Rosner 1978). We see that the surface brightness of the K star α Cen B is nearly 5 times greater than that of the more nearly solar-type α Cen A, and the quiet Sun falls between the two. Roughly speaking, these measurements show α Cen A to be emitting like the quiet Sun and α Cen B to be comparatively active. This is consistent with the general result for late-type dwarfs reported by the CfA Stellar Survey (Vaiana *et al.* 1981), viz., that low-mass main sequence stars in general emit with higher surface brightness than the Sun at X-ray wavelengths.

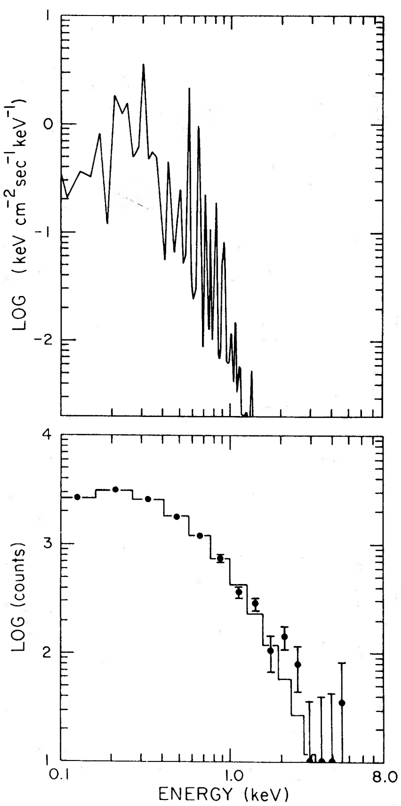

FIG. 2.—*Top*, inferred incident spectrum for α Cen from the IPC data. *Bottom*, observed spectrum obtained for α Cen with the IPC. Circles with error bars are the data points, and the histogram shows the calculated best-fit thermal spectrum; see text for details.

III. DISCUSSION

a) *Inhomogeneous Atmospheres*

The clear lesson to be learned from studies of the solar outer atmosphere is that inhomogeneity must be considered as a *fundamental* property (Vaiana and Rosner 1978; Withbroe and Noyes 1977). The complications which are encountered in descriptions of the solar atmosphere are inherent in the observed fact that the atmospheric structure is controlled by the magnetic field. It is the stochastic nature of magnetic flux eruption and the subsequent diffusion of those fields across the solar surface which are responsible for the observed mixture of open and closed, strong and weak, active and inactive X-ray emitting regions.

As a first approximation, the break from homogeneous, plane-parallel models can be initiated by assuming that the integrated emission in a particular line or passband derives from two types of corona, say "active" and "quiet." One would then write (see, e.g., Giampapa 1980; Cook, Brueckner, and Shipman 1980).

$$F_{\text{tot}} = f F_{\text{active}} + (1 - f) F_{\text{quiet}} ,$$

where f is a surface filling factor, which in practice will be analogous to the filling factor encountered in § III*b* below, and the F's are surface fluxes. Without additional constraints, a range of possible values will be obtained, just as is the case in the X-ray regime.

The fact that late-type dwarf stars appear to have activity cycles implies the added complication that observations taken at different times in different wavelength regimes may be difficult to assemble in a meaningful manner when attempting to construct a coherent model atmosphere. The *IUE* observations of α Cen reported by Ayres and Linsky (1980) imply that, in 1978 at least, the transition region surface fluxes of the two stars were nearly identical. Our measurements, taken two years later, show that the X-ray surface fluxes are different by a factor of 4. A possible interpretation of this difference is that the two stars have activity cycles which are not in phase, so that the *IUE* and *Einstein* observations may not be strictly compared, as a result of changes in the stars during the two years between the dates of data gathering. We caution, however, that a self-consistent model of the corona through the transition region has never been performed, so that the true meaning of these differences is somewhat uncertain.

b) *Coronal Models*

Alpha Cen A is close in spectral type to the Sun, having only small differences in stellar mass, metallicity, and evolutionary stage (Flannery and Ayres 1978) and only a modest difference in surface gravity. In modeling the outer atmosphere, it therefore seems reasonable to assume conditions similar to those on the Sun, viz., that there is a strong influence from the eruption of dynamo-generated magnetic fields and that the atmosphere is consequently highly inhomogeneous. We shall then be able to use results from recent solar studies to draw conclusions about the atmospheric and magnetic properties of α Cen A. We shall also discuss the *limitations* of loop atmosphere models as applied to unresolved coronae, given the present state of knowledge in this field (cf. Walter *et al.* 1980).

For the case of α Cen B, the arguments for a solar-type atmosphere are slightly less compelling, although there are strong indications from the initial *Einstein* stellar surveys that magnetic field–related coronae are common to essentially all late-type main sequence stars (Vaiana *et al.* 1981; Pallavicini *et al.* 1981). In the following discussion, we shall assume that the X-ray emission of α Cen B derives from a structured loop atmosphere, and we shall examine the conclusions which can be drawn from this assumption.

For an atmosphere consisting of closed loops of magnetically confined plasma, each loop is subject to the constraint imposed by the scaling law of Rosner, Tucker, and Vaiana (1978):

$$T = 1.4 \times 10^3 (pL)^{1/3} , \qquad (3.1)$$

where T, p, and L are the coronal temperature, base pressure, and loop length. In the solar case, these parameters are all measurable, and knowledge of any two of them is known to provide a reasonable estimate of the third for loops which are in hydrostatic equilibrium and which are not larger than the pressure scale height of the local corona.

For larger loops, Serio *et al.* (1981) have extended equation (3.1), finding that the scaling relation need only be modified by a multiplicative term:

$$T = 1.4 \times 10^3 (p_0 L)^{0.33} \exp\left[-0.04L\left(\frac{2}{s_H} + \frac{1}{s_p}\right)\right], \qquad (3.2)$$

where p_0 is the loop base pressure (since p now need not be constant throughout the loop), s_H is the energy deposition scale height for heating, and s_p is the pressure scale height. These constraints will allow us to draw conclusions about the range of allowed pressures in an unresolved stellar corona, which can then be compared with chromospheric and transition region models of these stars.

The total X-ray emission from an optically thin corona may be described by the general relation

$$L_x = \int n_e^2 P(T) dV , \qquad (3.3)$$

where n_e is the electron density and $P(T)$ is the density-independent portion of the plasma radiative loss function per cm^3 of plasma. We may set $V = 4\pi R_*^2 H f$, with H the emission scale height (whether limited by the loop size or by the atmospheric scale height) and $f \leq 1$ a filling factor which allows for the possibility that the emitting loops do not completely cover the stellar surface; it is either a surface or a volume factor, depending on the spatial location in the loop at which the emission originates and the field topology at that location. The quantity R_* is the stellar radius. Rewriting equation (3.3),

$$L_x = 4\pi R_*^2 f H p^2 (4k^2)^{-1} T^{-2} P(T) , \qquad (3.4)$$

we solve for p. The result, which is basically a rewriting of equation (3.3) and does not include the constraints (3.1) or (3.2), is

$$p = 2kT[F_x/fHP(T)]^{1/2} . \qquad (3.5)$$

We may now make use of the relation (3.2) in order to substitute for H in equation (3.5). The discussion separates naturally into two parts, depending on whether the exponent in brackets in equation (3.2) is negligible; this amounts to a division into loops which are completely filled with emitting material and those for which the exponential falloff of plasma density becomes a significant factor. As a shorthand description, we will refer to these two classes of loops as those which are, respectively, smaller than and greater than the pressure scale height.

i) *Loops Smaller than the Pressure Scale Height*

If we now include the constraint (3.1), which is the simpler form of equation (3.2) valid for the case $L < s_p$, then we have

$$H = 2L/\pi = 2.3 \times 10^{-10} T^3/p , \qquad (3.6)$$

which, inserted into equation (3.5), gives

$$pf = 3.3 \times 10^{-22} F_x/TP(T) . \qquad (3.7)$$

Equation (3.7) represents a locus of allowed values in the (p, f)-plane which would satisfy the observational constraints provided by measurements of L_x and T for the case of a loop atmosphere with $L < s_p$.

We may add another piece of information to equation (3.7). The scaling law (3.1) specifies a unique loop length L for each value of the coronal base pressure p (given the observational constraint of a fixed coronal temperature T). Therefore, we may assign a unique L-value to every position on the locus of points defined by equation (3.7). The end result is that, given a measurement of X-ray luminosity, coronal temperature, and any one of the three quantities p, f, or L, we may specify the remaining two quantities.[4]

[4] It is worth recalling at this point the assumptions which have gone into this statement. They are (i) that all of the loops are the same, (ii) that the loop size L is less than the pressure scale height $s_p = kT/mg$, and (iii) that the scaling law (3.1) holds.

The value of coronal base pressure determined here represents the value in the regions which are doing the emitting. Typical observations provide an average over the entire stellar surface, which would contain another multiple of the filling factor *f*.

ii) *Loops Larger than the Pressure Scale Height*

For the case in which we imagine a loop atmosphere in which all of the (identical) loops are larger than the pressure scale height, the use of equation (3.6) for the emission scale height is no longer appropriate. For large loops, the exponential falloff of pressure with height becomes significant, so that the loops may no longer be considered entirely filled with emitting plasma. In this case, the appropriate quantity to use for the emission scale height is just $\frac{1}{2}s_p$ (the factor $\frac{1}{2}$ derives from the fact that the emission falls off as n_e^2, whereas the pressure drops directly with n_e). We therefore make the substitution

$$H = \tfrac{1}{2}s_p = \tfrac{1}{2}(2kT/\mu g) \tag{3.8}$$

in the general formula (3.5), where $\mu \approx 1.4m_p$ is the average ion mass. The result is a new relation between the coronal pressure and the filling factor:

$$p^2 f = [4mgk/P(T)]F_x T \tag{3.9a}$$

$$= \{3.2 \times 10^{-35}/[P(T)(g_\odot/g)]\}F_x T \; . \tag{3.9b}$$

Equation 3.9 describes a line in the (p, f)-plane, representing the allowable locus of pressure and filling factor values which will satisfy the observing constraints on L_x and T, for loop atmospheres with $L > s_p$.

As in the case of the compact loop atmosphere, for which the constraint (3.7) holds, we may put a scale of loop sizes along the $p^2 f$ line of equation (3.9). It is necessary now to use the more general scaling law of Serio *et al.* (1981), i.e., equation (3.2), which contains an additional parameter, the heating deposition scale length s_H. This quantity is in general not known, so that it is not possible in general to assign a unique loop length for each given p of f value unless we have additional information about the heating mechanism.

iii) *The Approximation* $L = s_p$

It is of interest to note that the coronal filling factor has a uniquely determined value *if* the loop lengths are all just equal to the pressure scale height. While there is at this point no *a priori* reason why loop atmospheres would in general follow this constraint, it is at least instructive to examine what would be the consequences if this condition obtained. In that case both equations (3.7) and (3.9) would apply, so that we may solve for f:

$$f = [3.4 \times 10^{-9}/P(T)]F_x[T^3(g/g_\odot)]^{-1} \; . \tag{3.10}$$

Applying this technique to the Sun, we would conclude that the coronal filling factor is 0.09 and that the typical coronal structure is a loop of height $\sim 1 \times 10^{10}$ cm with a surface brightness of 3.7×10^5 ergs cm^{-2} s^{-1}. Such structures would be brighter than the quiet Sun but a factor of ~ 10 less than active region strength.

For α Cen A and B the same method gives coronal filling factors of 0.05 and 0.15, respectively, and surface brightness levels of 2.6×10^5 and 4.1×10^5 ergs cm^{-2} s^{-1}. The implication of this calculation may be that it is more the filling factor than the surface brightness which changes in going from α Cen A to the Sun to α Cen B, although the surface brightness does also correlate somewhat with the filling factor.

The same calculation may be performed for the case of the dMe flare star Proxima Cen, using the values quoted by Haisch *et al.* (1980). The observed mean surface flux of X-rays was $\sim 7 \times 10^5$ during the quiescent (nonflaring) phase, and the quiescent coronal temperature was $\sim 4 \times 10^6$ K. The location of the (f, p) point corresponding to these values is at $f = 0.19$ and $p = 3.8$. The X-ray surface brightness in the regions doing the emitting would be $\sim 4 \times 10^6$ ergs cm^{-2} s^{-1}, so that Prox Cen would, in this description, be substantially covered with solar-type active regions. Such a model would be consistent with the interpretation given by Haisch *et al.* for both the quiescent and flaring properties observed in X-rays for Prox Cen, including both the high surface flux of X-rays and the enhanced rate of flaring.

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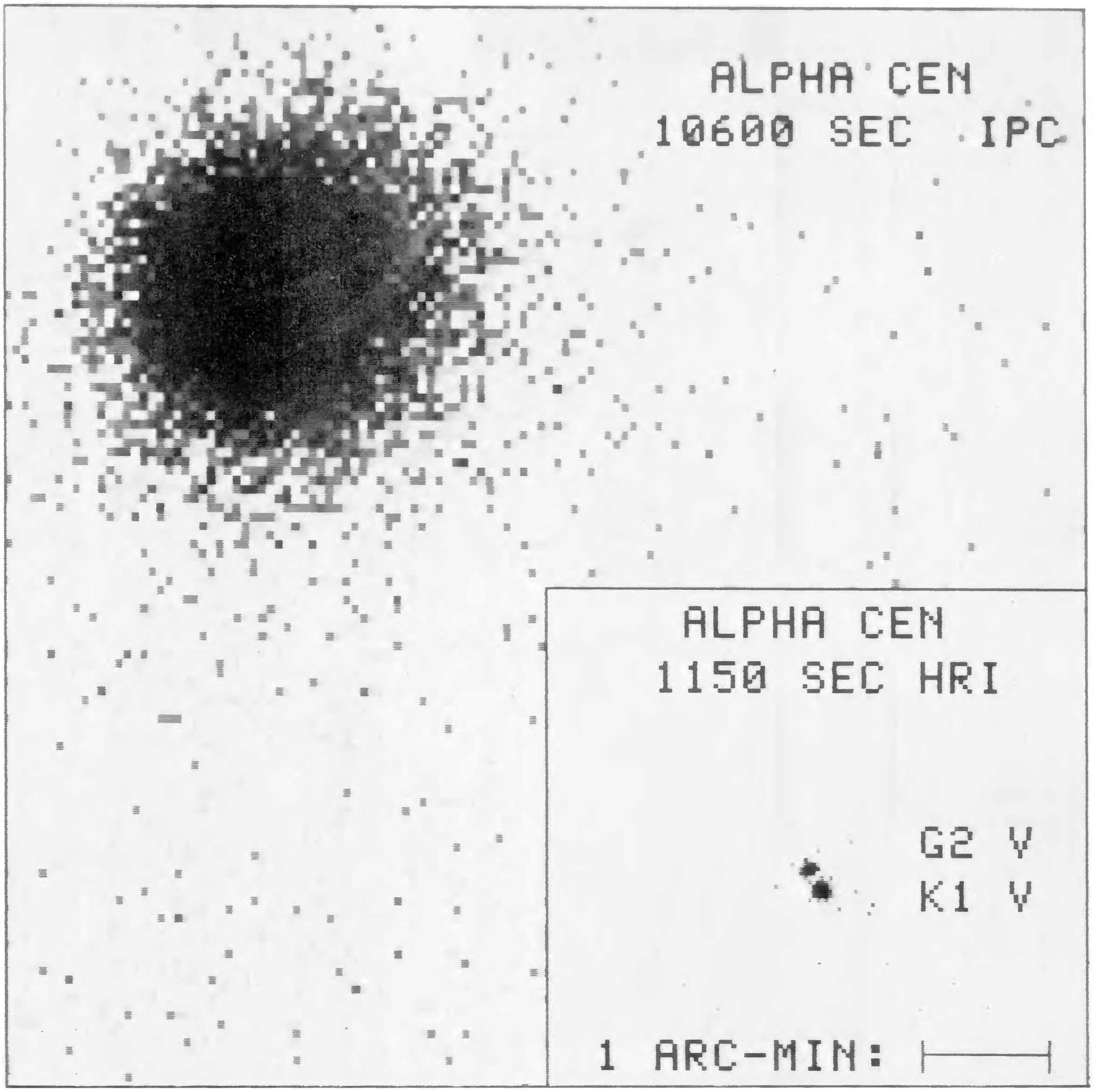

FIG. 1.—Combined IPC and HRI images of α Cen AB, with indicated exposure times. Both images are to the same scale

GOLUB *et al.* (*see* page 243)