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# *ROSAT* X-RAY DETECTION OF $\epsilon$ TAURUS: REVISITING THE CORONAL AND TRANSITION REGION EMISSION OF THE HYADES GIANTS

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## ABSTRACT

We report on a recent pointed X-ray observation of the Hyades giant $\epsilon$ Tau, obtained with the *ROSAT* PSPC. We confirm at higher significance the earlier *ROSAT* all-sky survey detection of this star, with an X-ray luminosity of $\sim 10^{28}$ ergs s$^{-1}$. $\epsilon$ Tau turns out to be the X-ray faintest among the four giants of the Hyades cluster, and the only one with no evidence of binarity. We rediscuss possible explanations, already put forward in previous studies, for the large spread in coronal and transition region emission observed among these stars. We revisit this issue in the light of our most recent knowledge on X-ray and UV emission properties of other Hyades and field stars.

*Subject headings:* open clusters and associations: individual (Hyades) — stars: coronae — stars: giant — X-rays: stars

## 1. INTRODUCTION

The giants of the Hyades cluster, namely $\theta^1$ Tau, $\gamma$ Tau, $\delta$ Tau, and $\epsilon$ Tau, are particularly interesting in several respects. The turnover points of the Hyades, around $B-V=0$, suggests that these off main-sequence stars have followed similar evolutionary tracks. Indeed, they have relatively similar spectral types (around K0 III), effective temperatures, gravities, masses, metallicities, and rotational velocities (Boesgaard, Heacox, & Conti 1977; Keenan & Pitts 1980; Lambert, Dominy, & Sivertsen 1980; Gray & Endal 1982), and therefore constitute a rather homogeneous (though small) sample of evolved stars. Despite this homogeneity, Baliunas, Hartmann, & Dupree (1983) reported *IUE* observations of these four giants showing a spread in chromospheric and transition region line flux not easily explicable by the standard mechanisms thought to control UV emission in cool stars. *Einstein* X-ray observations of the Hyades cluster (Stern et al. 1981; Micela et al. 1988) provided the detection of $\theta^1$ Tau, $\gamma$ Tau, and $\delta$ Tau, while $\epsilon$ Tau was not observed. Although the first three stars are known as spectroscopic binaries, Baliunas et al. (1983) and Micela et al. (1988) argued that the observed UV and X-ray emission originates from the K0 III primaries, and not from a companion, based on circumstantial evidences.

Most recently, Stern et al. (1992) reported the detection of $\epsilon$ Tau during the *ROSAT* All-Sky Survey. They did not detect $\delta$ Tau and suggest that long term variability may be partly responsible for the observed spread in X-ray luminosity in these apparently similar stars. In additon they point out that if stellar cycles are to be responsible for this spread, a simple extrapolation of the cycles observed in Ca II fluxes cannot entirely account for the dispersion in X-ray luminosity.

In this paper we report on a 1.5 ks pointed X-ray observation of $\epsilon$ Tau with the *ROSAT* Position Sensitive Proportional Counter (PSPC). This target has been specifically selected because no pre–*ROSAT* X-ray observation was available, and because it is the only star among the Hyades giants with no evidence of binarity; thus, its X-ray emission—with reasonable confidence—is not contaminated by contributions from lower mass companions. In § 2 we present our data and discuss the assumptions needed to compute the X-ray luminosity. In § 3 we discuss our results, in the broader context of the X-ray and UV emission level of the four Hyades giants.

## 2. X-RAY DATA AND RESULTS

The Hyades giant $\epsilon$ Tau was observed for 1541 s with the *ROSAT* PSPC on 1992 March 12. The MPE Standard Analysis Software System (SASS version 5.7) detected the target with "likelihood" (Cruddace, Hasinger, & Schmitt, 1988) of 15.7 and a count rate of $1.0(\pm 0.3) \times 10^{-2}$ counts s$^{-1}$ in the 0.1–2.4 keV energy band. The small number of detected counts ($\approx 15$, background-substracted) precludes any spectral analysis. In the following, we shall assume an optically thin thermal spectrum (Raymond & Smith 1977) with cosmic abundances, and a hydrogen column density of $10^{19}$ cm$^{-2}$.

In order to compare the X-ray emission level of $\epsilon$ Tau with that determined by *Einstein* from the other Hyades giants, we have computed *ROSAT* X-ray fluxes and luminosities in the 0.16–4.0 keV band. Assuming a single temperature Raymond-Smith spectrum with $T = 10^7$ K, typical of the giant stars observed by *Einstein* and studied by Schmitt et al. (1990), we find a X-ray flux at Earth of $f_X = 0.79 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$. We note that assuming a solar-like coronal temperature ($\log T = 6.5$) the X-ray flux would be $\sim 10\%$ lower. The X-ray luminosity computed upon adopting the mean distance of the cluster (45 pc) and $\log T = 7.0$ is $L_X = 1.9 \times 10^{28}$ ergs s$^{-1}$. Table 1 displays the X-ray fluxes and luminosities for $\epsilon$ Tau and the other three giants. The latter data are based on *Einstein* X-ray observations (Micela et al. 1988), and the same distance of 45 pc has been assumed for all the stars. Given the uncertainties in distance of the individual stars, we report also values of the ratio between X-ray and visible fluxes, $f_X/f_v$, a distance-independent quantity for low interstellar absorption.

## 3. DISCUSSION

Assuming for all the Hyades giants the nominal distance of 45 pc, the X-ray luminosity of $\epsilon$ Tau is $\approx 5$ times below that of

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TABLE 1

X-RAY FLUXES AND LUMINOSITIES FOR THE HYADES GIANTS

| Star | $f_X$ ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | $f_X/f_v$ | $L_X$ ($10^{29}$ ergs s$^{-1}$) |
|---|---|---|---|
| $\theta^1$ Tau (*Einstein*) .... | 29.1 ± 1.3 | $3.1 \times 10^{-5}$ | 7.0 |
| $\gamma$ Tau (*Einstein*) ..... | 14.6 ± 1.3 | $1.3 \times 10^{-5}$ | 3.5 |
| $\delta^1$ Tau (*Einstein*) .... | 4.3 ± 1.1 | $4.3 \times 10^{-6}$ | 1.0 |
| $\epsilon$ Tau ................ | 0.79 ± 0.26 | $6.4 \times 10^{-7}$ | 0.19 |

the faintest among the three other giants ($\delta$ Tau) and a factor ≈40 below that of $\theta^1$ Tau, the brightest in X-rays. We note that this factor may be influenced by the cross calibration between *Einstein* and *ROSAT*. However, a comparison of the plot of X-ray luminosity versus $B-V$ color for the Hyades stars reported by Micela et al. (1988) with that reported by Stern et al. (1992) rules out errors larger than 20%–30%. Our result for $\epsilon$ Tau—by a large measure the Hyades giant with the lowest X-ray luminosity—therefore confirms the large spread in coronal emission among the Hyades giants already noted by Baliunas et al. (1983) and by Micela et al. (1988), and suggests that a more careful study of the observed UV and X-ray emission from the Hyades giants is called for.

### 3.1. *Dwarf Companions*

We will first reconsider the possibility that the observed spread in emission levels may be the result of additional emission contributions from lower mass companions to the giants in binary systems.

For $\theta^1$ Tau, the spectral type of the secondary has been derived by Peterson et al. (1981) on the basis of lunar occultation measures. For $\delta$ and $\gamma$ Tau, estimates have been made by Baliunas et al. (1983) from the presence of an excess in the continuum UV emission near 1800 Å: In all three cases, the companion is likely to be a late F or G dwarf star. No indication of binarity exists for $\epsilon$ Tau; in particular, its radial velocity measurements do not support the existence of an unseen companion (Griffin et al. 1988).

In order to ascertain if the observed chromospheric, transition region, and coronal emission for $\theta^1$, $\delta$, and $\gamma$ Tau is consistent with the spectral type of the secondaries, we have considered the sample of nine Hyades dwarfs (spectral types F5–G6) reported in the recent study of Caillault, Vilhu, & Linsky (1991). In Figure 1 we show scatter plots of the X-ray luminosity versus the C IV (1550) line luminosity (Fig. 1*a*), and versus the Mg II $h+k$ luminosity (Fig. 1*b*), for both the Hyades giants (Baliunas et al. 1983) and the Hyades solar-like dwarfs in Caillault et al. (1991). First, we note that the X-ray luminosities of these stars range from $1.1 \times 10^{29}$ to $5.8 \times 10^{29}$ ergs s$^{-1}$, which is typical of the Hyades solar-like stars (Micela et al. 1988), and is comparable to the X-ray luminosities of the Hyades giants (with the exception of $\epsilon$ Tau). More precisely, the X-ray luminosity of $\delta$ Tau is slightly below the mean value for the Hyades solar-like stars, while $\gamma$ Tau and $\theta^1$ Tau—the brightest in X-rays—lie in the extreme high luminosity tail of the X-ray luminosity function for the same sample of dwarf stars, reported by Micela et al. (1988). We demand the issue of possible time variability of the observed X-ray emission to the next subsection.

A similar indication comes from the comparison of the C IV (1550) line luminosities (abscissa in Fig. 1*a*): The two giants detected in C IV ($\theta^1$ and $\gamma$ Tau) show line luminosities comparable to those of the late F dwarfs reported by Caillault et al. (1991); in the case of the nondetected stars $\delta$ and $\epsilon$ Tau, we can only state that the upper limits on their C IV line luminosities are also comparable to detections or upper limits for C IV emission from the Hyades G dwarfs, as reported by the same authors. In the hypothesis that the observed X-ray and UV emission of $\theta^1$ and $\gamma$ Tau comes from the dwarf secondaries of these systems, we note that since the X-ray and C IV line luminosities are similar, also the average surface fluxes, or the ratios of the X-ray and C IV emission to bolometric luminosities, are typical of the Hyades solar-like stars.

These results are however belied by the comparison of the chromospheric emission level (Fig. 1*b*): The luminosity in the Mg II $h+k$ chromospheric lines of the Hyades dwarfs considered by Caillault et al. (1991) varies from 1.5 to $7.7 \times 10^{29}$ ergs s$^{-1}$, a factor 10 lower on average than the Mg II line luminosity of the Hyades giants (which lie in the range 2.9–$4.8 \times 10^{30}$ ergs s$^{-1}$), including $\epsilon$ Tau. The same behavior holds for the luminosity in the chromospheric O I triplet ($\lambda\lambda$1302, 1305, 1306). These latter results are difficult to understand in any way other than that the chromospheric emission is due—

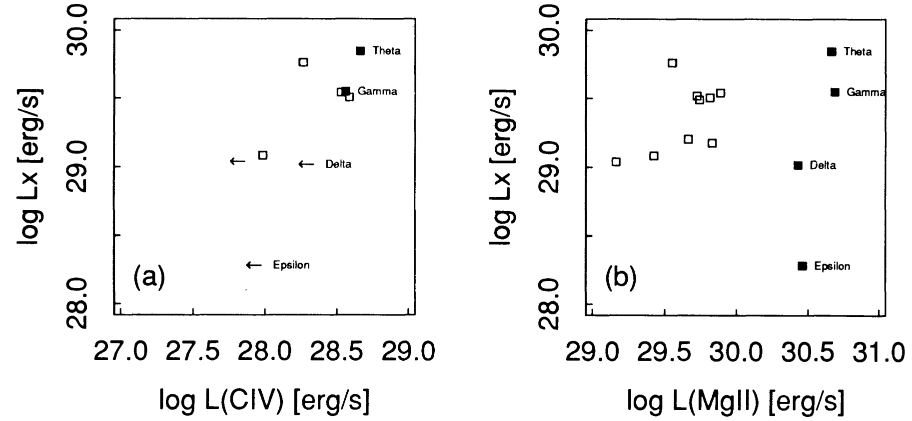

FIG. 1.—(*a*) Scatter plot of X-ray luminosity vs. C IV (1550) line luminosity for the Hyades giants (*filled squares*, plus two upper limits in C IV, and relative names), and for the Hyades solar-type dwarfs (*open squares*, plus one upper limit in C IV) studied by Caillault et al. (1991). Note that these two samples cover the same range of luminosities both in X-rays and in C IV. (*b*) Scatter plot of X-ray luminosity vs. Mg II $h+k$ line luminosity for the same two samples as above. Note that the Hyades giants show consistently higher Mg II line luminosities than the Hyades dwarfs.

essentially entirely—to emission from the giants alone, and are consistent with the indications provided by the width of Ca II and Mg II line emission cores (Baliunas et al. 1983).

However, we are not as certain about the origin of the transition region and coronal emission. In oder to reconcile the above results, we next consider the following hypothesis: We suppose that in the short-wavelength UV spectra of $\theta^1$ and $\gamma$ Tau (as observed by *IUE*) we are seeing a mixture of chromospheric line emission (e.g., the O I triplet) from the primaries, and transition region line emission (e.g., the C IV resonance doublet) from the dwarf secondaries. Then, there are some points to consider:

1. If this hypothesis were true, we then would need to explain why the giants with the most luminous chromospheres ($\theta^1$ and $\gamma$ Tau) are associated with companion dwarf stars which are also brighter in C IV and in X-ray emission. Unfortunately, this peculiarity is not a decisive point because it may be simply the result of chance coincidence (given the fact that we are dealing with only four objects and two upper limits in the C IV emission).

2. Given the higher luminosities in chromospheric limits of the giants with respect to the dwarf stars that this hypothesis implies, the transition region and coronal emission from the giants should not scale with the corresponding chromospheric emission, since otherwise the contribution from the giants would be most prominent. For example, if we take $\epsilon$ Tau as an archetype of the Hyades giants, we find that its Mg II $h + k$ luminosity is a factor 4 higher than the corresponding luminosity of the chromospherically brightest F dwarf, while its X-ray luminosity is $\sim 20$ times lower. On the other hand, the spread in Mg II line luminosity among the giants is only a factor 1.8, to be compared with a factor of $\sim 40$ range in X-ray emission levels. If the observed emission were due entirely to the giants, an highly nonlinear relationship between the chromospheric and coronal emission level would be required ($L_{\rm X} \approx L^6_{\rm Mg\,II}$): such a relationship is not observed in field stars (Ayres, Marstad, & Linsky 1981), and seems to us rather unlikely. Similar arguments can be made based on the C IV (or Si IV) line emission levels, but these cannot be made as quantitative because $\delta$ and $\epsilon$ Tau have not been detected in any of the transition region lines.

3. Under the above hypothesis, the most luminous X-ray sources among the giants should have X-ray spectral characteristics typical of the young solar-type dwarf stars. This expectation is supported by the study of Schmitt et al. (1990), who have found in a X-ray spectral survey of late-type stars observed by *Einstein* that $\theta^1$ Tau—the only Hyades giant included in that survey—has a non-isothermal corona, typical of active dwarf stars and observed in none of the other field giant stars in their sample (see, however, the new *ROSAT* observations of evolved stars reported by Maggio, Sciortino, & Harnden 1993).

4. The final consequence of our hypothesis is that the Hyades K0 giants, in particular $\epsilon$ Tau, located just at the red edge of the Hertzprung gap in the H-R diagram, would have chromospheric radiative losses which exceed their coronal emission levels by more than two orders of magnitude, in contrast to the Hyades solar-type dwarf stars, which show a ratio between the Mg II $h + k$ line luminosity and the X-ray luminosity ranging from 0.6 to 4.5. This behavior is reminiscent of the change in character of the field giants upon crossing the so-called "transition region (and coronal) dividing line" (Linsky & Haisch 1979; Haisch et al. 1990): In fact, field stars to the right of this locus in the H-R diagram, which occurs approximately at spectral type K3 III, show only a chromospheric spectrum, with little evidence of plasma at transition region or coronal temperatures.

### 3.2. *Long-Term Variability*

Saar & Baliunas (1992) report for the Hyades giants a monitoring of the Ca II emission over a 7 year period (1984–1990) and note that, at variance from the other three giants, $\epsilon$ Tau has no evidence for a cycle. They suggest for this star the analog of a solar Maunder minimum status.

The ROSAT survey (Stern et al. 1992) detected $\epsilon$ Tau but did not detect $\delta$ Tau at the same sensitivity. The upper limit on the X-ray luminosity of $\delta$ Tau is $\approx 3$ times below the *Einstein* detection. Though strongly suggestive of long-term variability, this result might need further confirmation given the low signal-to-noise ratio of the survey data in the Hyades region. In addition, these authors found the X-ray luminosity of $\theta^1$ Tau at a level 1.5–2 times above the *Einstein* level, and a factor 5 above that of the brightest solar-like Hyades dwarf. Again, this result is suggestive of variability.

A similar suggestion has been recently reported by Sciortino & Micela (1992), who have found evidence of long-term variability in the X-ray emission of $\theta^1$ Tau, for which two *Einstein* observations are available, separated by about $1\frac{1}{2}$ yr.

Variability seems therefore to be present among these stars, though its characterization needs further observations. It might well be responsible for the large spread observed in X-ray and UV emission, possibly in conjunction with other effects, like contribution from dwarf companions, as discussed in the previous section. The firmer statement, however, requires a much deeper knowledge of the time scales and amplitudes involved in the variability.

### 3.3. *Different Evolutionary Phases?*

The observed differences in the UV and X-ray emission levels would not be so intriguing if the four giants were not in the same evolutionary phase. In particular, we will consider the possibility that the two stars with the highest activity level ($\theta^1$ and $\gamma$ Tau) are first-crossing giants, just at the exit of the Hertzprung gap, while the other two ($\delta$ and $\epsilon$ Tau) are He-burning clump giants. Since there is no evidence of a significant spread in stellar birth times for the Hyades, the above hypothesis requires that the four stars would have slightly different masses. In fact, it is unlikely that all the evolved stars in this cluster have exactly the same mass. On the other hand, we should explain why stars of different masses but same age occupy so close positions in the H-R diagram. Considering the evolutionary time scales in the models of Maeder & Meynet (1988) for stars with masses near the cluster turn-off mass ($\sim 2.2\ M_\odot$), two conclusions can be drawn: (1) Differences of few tenths of a solar mass may be sufficient to justify our present hypothesis; in fact, while a 2 $M_\odot$ star at the age of the Hyades ($8 \times 10^8$ yr) is still on the main sequence, a 2.5 $M_\odot$ star is already ascending the giant branch for the second time. (2) Stars in this range of masses spend most of their time (1–$2 \times 10^8$ yr) as clump giants, rather than as first-ascent giants (6–$20 \times 10^6$ yr), hence the probability to observe stars in different evolutionary phases is low ($< 10\%$).

Although a slight mass difference cannot be ruled out, none of the presently available information is able to provide a clear evidence either pro or con this hypothesis. In fact, only one light curve is visible for all the three spectroscopic binaries, and hence no direct mass estimate is possible (Griffin & Gunn 1977). Moreover, the $^{12}C/^{13}C$ ratios and Li abundances determined by Gilroy (1989) agree within the 15% uncertainties, and in any case it is still unclear whether these measurements may provide clues toward assessing the evolutionary phase of these stars. Even the study of Gray & Endal (1982) on the angular momentum history of the Hyades K giants do not allow us to draw unambiguous conclusions on this issue. Finally, any difference in the bolometric luminosities of these stars, which may be expected if the stellar masses are different, is masked by the 30% uncertainty in individual parallax measurements.

## 4. CONCLUSION

In this paper we have addressed the problem of the large spread in coronal and transition region emission from the Hyades giants, a presumably homogeneous coeval sample of evolved stars. Though this problem has puzzled stellar X-ray astronomers since the *Einstein* observation of three out of the four stars in the sample, the new information provided by *ROSAT* observations and the further analysis conducted on *Einstein* data (see Schmitt et al. 1990) have suggested a revisitation of this topic and further investigation on the possible origin of the X-ray and UV emission themselves. In particular, we have considered three possibilities, i.e., a contribution to the observed X-ray and UV emission from the dwarf companions in the binary systems, the variability of these stars and possible differences in the evolutionary phases. We have rediscussed more in detail the first possibility, although it had been previously generally rejected by other authors, because we feel it cannot be excluded in the light of the most recent results. We point out that also variability seems to play an important role in this intriguing problem, and variability itself seems the most reasonable explanation for the discrepancies between *Einstein* and *ROSAT* observations. Further X-ray observations should aim at a better characterization of the time variability and at providing spectral information able to discriminate on the origin of the X-ray emission. Finally, the better estimates of the stellar distances, expected from the Hipparcos mission, will allow us to test the evolutionary hypothesis.

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