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DIGGING IN THE CORONAL GRAVEYARD: A *ROSAT* OBSERVATION OF THE RED GIANT ARCTURUS

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ABSTRACT

A deep exposure of the bright star Arcturus (α Bootis: K1 III) with the *Röntgensatellit* (*ROSAT*) failed to detect soft X-ray emission from the archetype "noncoronal" red giant. The 3 σ upper limit in the energy band 0.1–2.4 keV corresponds to an X-ray luminosity of less than 3×10^{25} ergs s^{-1}, equivalent to a coronal surface flux density of less than 1×10^{-4} solar.

The nondetection safely eliminates coronal irradiation as a possible mechanism to produce the highly variable He I λ10830 feature and emphasizes the sharp decline in solar-like coronal activity that accompanies the evolution of low-mass single stars away from the main sequence.

While the most conspicuous object in the *ROSAT* field of view was not visible in X-rays, at least one fainter star is among the ≈60 sources recorded: the δ Sct variable CN Boo, an A8 giant in the UMa Stream.

Subject headings: stars: coronae — stars: individual (α Bootis, CN Bootis) — stars: X-rays

1. INTRODUCTION

One of the triumphs of modern X-ray astronomy was the recognition that solar-like hot coronae ($T \approx 10^6$ K) are nearly ubiquitous among stars in the cool half of the Hertzsprung-Russell diagram (Vaiana et al. 1981). At the same time, one of the great puzzles of modern X-ray astronomy is the striking lack of prominent coronal sources in the corner of the H-R diagram occupied by the single red giants, across a "dividing line" near K0 III (originally recognized in C IV λ1549: Linsky & Haisch 1979).

One school of thought (Ayres et al. 1981) argues that the dividing line is an accident of stellar evolution, which coincidentally juxtaposes two very different populations of stars (moderate-mass and low-mass) in neighboring areas of the giant branch; the two populations have quite divergent histories of hydromagnetic "dynamo" activity (e.g., Parker 1970) leading to a large contrast in coronal properties on either side of the apparent boundary.

A second school of thought (Antiochos, Haisch, & Stern 1986) proposes that the X-ray deficiency of the red giants results from an instability promoted by their generally lower surface gravities (compared with the F-G coronal "yellow" giants): it inhibits the formation of closed magnetic *loops* in which the excitation and trapping of 10^6 K gas is known to occur on the Sun. In the authors' scenario, the mechanical energy that otherwise would power the hot corona instead is diverted into the propulsion of the strong cool (10^4 K) *winds* that typify the K-type giants (e.g., Haisch, Linsky, & Basri 1980).

Now, with the advent of *ROSAT*, it is possible to continue the exploration of the coronal/noncoronal dichotomy which was begun in a preliminary way during the *Einstein* era a decade ago. Arcturus (HD 124897; α Bootis: K1 IIIb CN−1) is the archetype noncoronal giant (Ayres et al. 1981) and the best candidate for *ROSAT* to seek a "ghostly" corona in the depths of the coronal graveyard.

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2. PREVIOUS X-RAY STUDIES OF ARCTURUS

There was significant interest in the question of red-giant coronae, even prior to the discovery of the coronal dividing line during the *Einstein* era.

For example, the low-mass ($M \lesssim 2\ M_{\odot}$) red giants are a luminous component of the galactic stellar population and any significant coronal emission potentially could contribute to the cosmic diffuse soft X-ray background (Hills 1973).

In addition, K giants like Arcturus exhibit He I λ10830 absorption; often quite variable and occasionally in emission (O'Brien & Lambert 1979, hereafter OL). The lower level of the transition is 20 eV above the ground state and it is difficult to excite without some hot gas in the outer atmosphere (OL): either directly to populate the lower level of the transition by collisions; or indirectly to maintain a reservoir of highly excited atoms by recombination of chromospheric helium photoionized by coronal EUV radiation (Zirin 1975).

The first attempt to record coronal X-ray emission from Arcturus was by Margon, Mason, & Sanford (1974) using the University College London X-ray telescope cluster on *OAO 3* (*Copernicus*). The limiting X-ray luminosity reported by the authors in the bandpass 0.1–1 keV for a solar-temperature source (10^6 K) was less than 5×10^{31} ergs s^{-1}. At about the same time, sounding rocket flights by Cruddace et al. (1975) failed to detect Arcturus at a luminosity of less than 1×10^{30} ergs s^{-1} in the energy range 0.075–2 keV, while Mewe et al. (1975) obtained a narrow-band (0.2–0.28 keV) limit of $< 5 \times 10^{28}$ ergs s^{-1} with the *Astronomical Netherlands Satellite*. A 0.25–2 keV luminosity of 1×10^{30} ergs s^{-1} would be expected if the red giant had a coronal surface flux density (ergs cm^{-2} s^{-1} at the star) similar to that of the Sun. While these early X-ray experiments were not particularly sensitive by modern standards, the upper limits on coronal emission from Arcturus were sufficiently good to eliminate the red giants as a candidate for a discrete-source explanation of the diffuse soft X-ray background (e.g., Cruddace et al. 1975).

In the late seventies, the NASA High Energy Astrophysics Observatories (*HEAO 1* and *2*) brought significant improvements in sensitivity. Nevertheless, Arcturus was not detected during the *HEAO 1* all-sky survey (e.g., Ayres et al. 1979). The 3 σ upper limit for the Low-Energy Detectors (0.15–3 keV) was of order 3×10^{29} ergs s^{-1}. Subsequently, Arcturus was observed with the *HEAO 2* (*Einstein*) Imaging Proportional Counter for 1.6 ks in early 1980 (Ayres et al. 1981) and a year later with the High Resolution Imager for 13 ks (Ayres, Simon, & Linsky 1982). In neither case was a source detected at the position of the red giant. The 3 σ upper limits correspond to luminosities of less than 2×10^{27} ergs s^{-1} (IPC) and less than 3×10^{26} ergs s^{-1} (HRI), assuming a solar-like spectrum and negligible interstellar absorption. The absence of Arcturus in the *Einstein* exposures contrasts with the easy detection of the nearby solar-type dwarf α Cen A (G2 V) at a level of 1×10^{27} ergs s^{-1} (Golub et al. 1982), comparable to the average Sun. Thus, the luminous red giant—with a surface area 700 times that of a G dwarf—emits less X-rays than the Sun or α Cen A.

Most recently, Arcturus was the target of an 8 ks pointing with the ESA *EXOSAT*. No sources are indicated in the *EXOSAT* catalog for the map obtained with the high-resolution ($\approx 10''$) X-ray telescope and channel multiplier array (CMA) detector. An upper limit for that observation has not been reported in the literature, but the approximate 3 σ sensitivity is 2×10^{-14} ergs cm^{-2} s^{-1} (0.04–2 keV; e.g., de Korte et al. 1981), corresponding to a luminosity of less than 3×10^{26} ergs s^{-1}. The large-area, medium-energy proportional counter array (ME) on *EXOSAT* did record significant counts during the Arcturus pointing, but the hard energy range (1.5–50 keV), wide field of view ($45' \times 45'$), and lack of confirmation in the CMA render an association with Arcturus quite unlikely.

3. *ROSAT* OBSERVATIONS

3.1. *Deep PSPC Pointing*

The circumstances of the *ROSAT* observation of Arcturus are summarized in Table 1. It was conducted in 1990 mid-July during instrument verification activities prior to the all-sky survey. The total exposure time was 18.6 ks, divided into 14 separate pointings over a 4-day period. The prime Position Sensitive Proportional Counter (PSPC-A) has an energy range of $\sim$0.1–2.4 keV, and a modest degree of energy resolution ($\Delta E/E \approx 0.5$). A full description of the characteristics and performance of the *ROSAT* X-ray telescope and PSPC can be found in Trümper (1983) and Pfeffermann et al. (1987).

Figure 1 illustrates the central, relatively unvignetted, portion of the PSPC image. The areas recorded in the historical IPC and HRI frames are outlined for comparison. The average background near field center was 1.9 counts per $0.25' \times 0.25'$ pixel.

3.2. *Nondetection of Arcturus*

There is no significant emission at the position of Arcturus. Indeed, no significant sources are detected in the central 5′ of the field. We established a 3 σ upper limit of 7×10^{-4} counts s^{-1} for the total energy range (0.1–2.4 keV) by applying a maximum-likelihood source-detection algorithm.

The corresponding flux upper limit depends sensitively on the assumed spectrum and its attenuation by neutral hydrogen along the line of sight, primarily in the red-giant wind. McClintock et al. (1978) established $N_H \lesssim 5 \times 10^{18}$ cm^{-2} in the direction of Arcturus through an analysis of high-resolution *Copernicus* scans of the circumstellar absorption feature in the core of the chromospheric H I Lyα emission. That limit is consistent with the mass loss rate of *ionized* material in the wind of Arcturus—whose thermal radio emission Drake & Linsky (1986) directly measured with the Very Large Array—if the hydrogen in the wind is more than $\sim$75% ionized. A moderate degree of hydrogen ionization is consistent with the fact that circumstellar absorptions are seen clearly in the Mg II *h* and *k* resonance lines but not in Ca II H and K, suggesting that the calcium is mostly Ca^{++} in the wind (see, e.g., McClintock et al. 1978).

Assuming that Arcturus is a solar-temperature source ($\log T \approx 6.0$) with $\log N_H \approx 18.7$, the conversion factor (to obtain the *unattenuated* flux) is $\sim 3 \times 10^{-12}$ ergs cm^{-2} $counts^{-1}$ based on in-flight calibrations of the PSPC-A. Accordingly, the 3 σ upper limit is $\sim 2 \times 10^{-15}$ ergs cm^{-2} s^{-1} at Earth, equivalent to a luminosity of 3×10^{25} ergs s^{-1} at the 11 pc distance of Arcturus.

As in Ayres, Simon, & Linsky (1982), we again use the solar twin α Cen A as a comparison against which to gauge the limiting X-ray flux of Arcturus. The α Cen A/B system appears (unresolved) in the *ROSAT* all-sky survey with a PSPC count rate of 4.9 ± 0.1 counts s^{-1}. Applying the X-ray luminosity ratio measured by Golub et al. (1982) with the *Einstein* HRI, $f_A/f_B \approx 0.4$, we estimate a PSPC count rate of 1.4 counts s^{-1} for α Cen A. Comparing that count rate to the Arcturus upper limit, and compensating for the radii and distances of the stars, we find that Arcturus displays a coronal surface flux density of less than 1×10^{-4} that of the solar surrogate.

3.3. *Other X-Ray Sources in the Arcturus Field*

Although Arcturus was absent, the source-finding algorithm identified $\approx$60 positions of enhanced counts in the PSPC field. A search through a variety of catalogs including stars (SAO, HD, BSC, Wooley, etc.), infrared sources (IRAS Point Source catalog, Serendipitous Survey, etc.), and 6 cm radio sources (Becker, White, & Edwards 1991) uncovered very few obvious counterparts at other wavelengths. The "novelty" of the deep

TABLE 1

DESCRIPTION OF OBSERVATION

Observation Number	Dates	Exposure Time (s)	Field Center (α_{2000}, δ_{2000})	3 σ Upper Limit Count Rate[a] (cts s^{-1})
CA150018.........	1990 July 18–21	18,605	213°92, +19°19	7×10^{-4}

[a] Energy range: 0.1–2.4 keV.

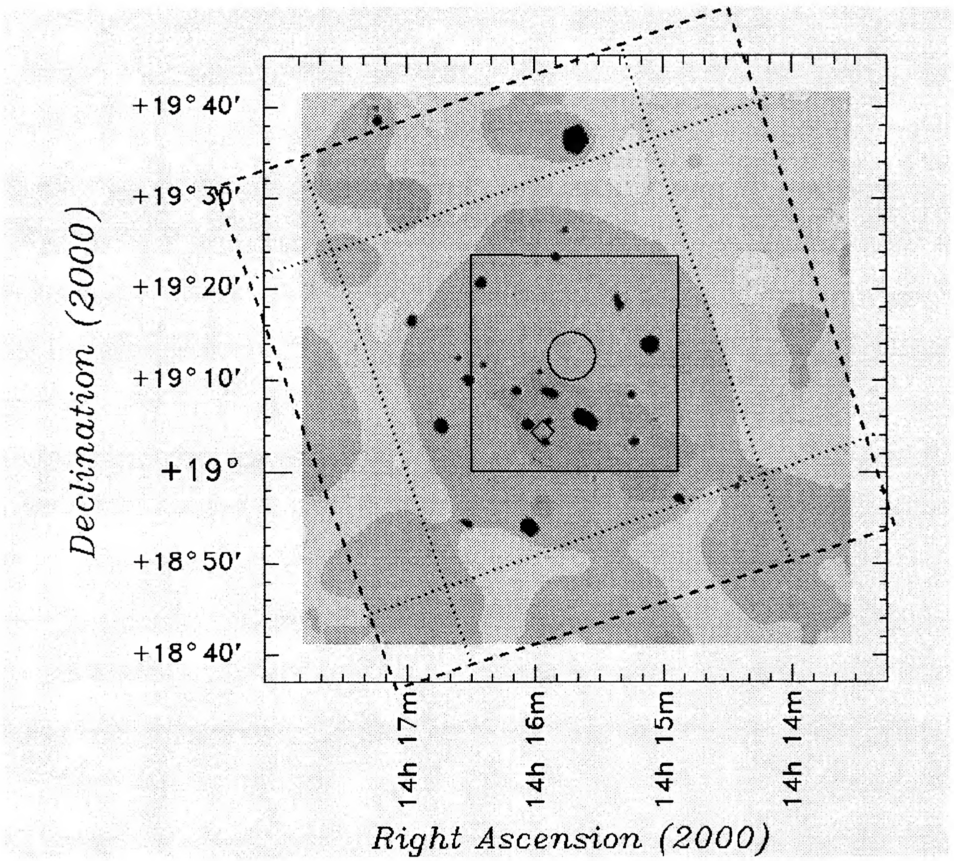

FIG. 1.—Representation of deep PSPC image of the Arcturus field emphasizing the structure of the low-level diffuse background, and depicting the positions of the ≈20 significant detections in the central 1° of the full 2° field. The background was established by median filtering to remove the sources and smoothing the result to highlight the large-scale structure (note the ribs of the window support mesh). The inclined dashed box depicts the field-of-view of the 1980 *Einstein* IPC observation of Arcturus (and the IPC window support structure), while the inner box depicts the field of view of the 1981 HRI pointing. A small diamond marks the position of the only detection in the two *Einstein* observations which achieved the significance criterion of the 2E catalog (3.5 σ above background). The solid circle—5′ in diameter, centered on the position of Arcturus—is devoid of sources. The moderately strong detection at the bottom of the frame (near 14^h16^m $+18°54'$) is coincident with the sixth-magnitude star CN Boo (A8 III), a δ Sct variable and a member of the young Ursa Major Stream.

X-ray sky in the Arcturus field is consistent with the experience of the *Einstein* Extended Deep Survey (Primini et al. 1991). The EDS fields were located at high galactic latitudes (like Arcturus: $b^{\rm II} = 69°$), with a typical limiting sensitivity (4.5 σ) of $\approx 5 \times 10^{-14}$ ergs cm^{-2} s^{-1} (comparable—but poorer—than our *ROSAT* image). Approximately 25% of the EDS sources can be attributed to faint ($V > 10$) stars, but the bulk of the detections are associated with previously uncataloged extragalactic objects, mostly QSOs.

While the majority of the sources in the *ROSAT* image cannot be identified readily, the fourth brightest ($\approx 10^{-2}$ counts s^{-1}) is coincident with a sixth-magnitude star, the δ Sct variable CN Bootis (HD 124893: A8 III).

CN Boo is noteworthy because it is a member of the very young UMa Stream and thus might be considered a candidate for enhanced coronal activity despite the fact that A-type stars as a rule are weak X-ray emitters (e.g., Vaiana et al. 1981). Schmitt et al. (1990) recently surveyed the X-ray properties of UMa Stream stars based on the historical collection of *Einstein* IPC frames. Of four UMa Stream A giants that fell intentionally or fortuitously in IPC fields, two were significant X-ray sources, and one of the two nondetections was CN Boo (falling within the 1980 IPC frame centered on Arcturus). CN Boo appears in the *ROSAT* field at a flux corresponding to 1×10^{28} ergs s^{-1} at its distance of ≈ 50 pc, very comparable to the two *Einstein* detections (α Oph [A5 III; 1×10^{28}] and β Eri [A3 III; 8×10^{28}]).

CN Boo is an extremely soft source: virtually all of its counts are in the energy band below 0.5 keV. Possibly it obeys the cool-corona hypothesis by which Simon & Drake (1989) explain the peculiar X-ray "deficiencies" (relative to C IV λ1549) of the early-F stars.

4. DISCUSSION

The significance of the nondetection of Arcturus in the deep *ROSAT* pointing is twofold: (1) for all intents and purposes solar-like coronal activity has faded beyond view on the old highly evolved single red giant; (2) the variable He I λ10830 feature of Arcturus and other K giants very likely derives from an entirely different class of "activity" than the magnetic variety that governs the solar outer atmosphere.

Regarding the first point: it appears that the coronal activity of a normal $\approx 1\ M_\odot$ star experiences a rapid decline during the first 10^9 yr of evolution on the main sequence (see, e.g., Wolff, Boesgaard, & Simon 1986), followed by a more gradual decay during the bulk of the $\approx 10^{10}$ yr MS lifetime, and ends in a second period of rapid decline during the post–main sequence phase. The culprit very likely is the impact on the rotationcatalyzed magnetic activity of the inexorable spindown of the star: angular momentum is shed by the magnetized coronal wind during the MS phase (e.g., Durney 1972), and redistributed internally during the subsequent rise into the giant branch (Endal & Sofia 1979).

That path will be followed by single, low-mass stars. However, deviations can be expected for low-mass stars in close binary systems which ultimately can tap the angular momentum reserves in the orbit itself (via tidal torquing); and for moderate- and high-mass stars ($M \gtrsim 2\ M_{\odot}$) whose short resident times on the MS and lack of magnetized coronal winds protects their supplies of angular momentum until P-MS evolution carries them into the (magneto-) convective region of the H-R diagram.

Regarding the second point: Cuntz & Luttermoser (1990) recently simulated the formation of the He I λ10830 feature of Arcturus in a model chromosphere bathed by coronal EUV radiation. The authors reported that an unattenuated flat-spectrum flux corresponding to 2×10^{-13} ergs cm^{-2} s^{-1} (at Earth) in the energy band below the He I edge at 504 Å was capable of reproducing a 10830 Å absorption like that observed ($\lesssim$100 mÅ equivalent width). However, the authors have indicated (D. G. Luttermoser 1990, private communication) that their conversion from observed flux at Earth to mean intensity at the star in the He I photoionization continuum suffered an inadvertent numerical error of a factor of 50. Thus, the true EUV flux at Earth required to explain the He I absorption within the coronal-irradiation hypothesis is more like 1×10^{-11} ergs cm^{-2} s^{-1}. The PSPC upper limit safely eliminates that possibility for any reasonable coronal spectrum with $T \gtrsim 10^5$ K. An alternative mechanism to produce the highly variable He I features—and the main subject of the Cuntz & Luttermoser work—are stochastic shocks formed by the propagation of long-period acoustic waves into the tenuous layers of the outer atmosphere.

The question arises whether future X-ray missions—the Advanced X-ray Astrophysics Facility in particular—can improve upon the *ROSAT* nondetection of Arcturus. As the sensitivity of X-ray imagers improves, source confusion becomes more of a problem: *ROSAT* has revealed more than 20 sources within a half-degree of Arcturus, whereas previous missions have cataloged only one. The high spatial resolution of the AXAF telescope should help in that regard, while the source spectrum can discriminate between a genuine solar-like corona and a coincidentally placed extragalactic object. Nevertheless, even a future positive detection of a small amount of 10^6 K plasma in the outer atmosphere of the old red giant would be a moot point: the extremely sensitive observation by *ROSAT* already indicates that the red-giant region truly is a graveyard as far as solar-like coronal activity is concerned.

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