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Final Report for

"A Deep X-Ray Survey of the Pleiades Cluster and

The B6-A3 Main Sequence Stars in Orion"

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I have attached to this report copies of the first pages of two articles which have appeared in the Astrophysical Journal. These articles represent most, but not all, of the work which we will have done with these data. One other paper on Orion (analyzing lower-mass stars) has already been submitted and is currently in the refereeing process, while another paper on the Pleiades (analyzing the spectral and temporal properties of the solar-type stars) is in the process of being written; we expect it will be submitted before the end of the year.

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A DEEP IMAGING SURVEY OF THE PLEIADES WITH *ROSAT*

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ABSTRACT

We have obtained deep *ROSAT* images of three regions within the Pleiades open cluster. We have detected 317 X-ray sources in these *ROSAT* PSPC images, 171 of which we associate with certain or probable members of the Pleiades cluster. We detect nearly all Pleiades members with spectral types later than G0 and within 25 arcminutes of our three field centers where our sensitivity is highest. This has allowed us to derive for the first time the luminosity function for the G, K, and M dwarfs of an open cluster without the need to use statistical techniques to account for the presence of upper limits in the data sample. Because of our high X-ray detection frequency down to the faint limit of the optical catalog, we suspect that some of our unidentified X-ray sources are previously unknown, very low-mass members of the Pleiades.

A large fraction of the Pleiades members detected with *ROSAT* have published rotational velocities. Plots of L_X/L_{Bol} versus spectroscopic rotational velocity show tightly correlated "saturation" type relations for stars with $(B-V)_0 \geq 0.60$. For each of several color ranges, X-ray luminosities rise rapidly with increasing rotation rate until $v \sin i \simeq 15$ km s^{-1}, and then remain essentially flat for rotation rates up to at least $v \sin i \simeq 100$ km s^{-1}. The dispersion in rotation among low-mass stars in the Pleiades is by far the dominant contributor to the dispersion in L_X at a given mass.

Only about 35% of the B, A, and early F stars in the Pleiades are detected as X-ray sources in our survey. There is no correlation between X-ray flux and rotation for these stars. The X-ray luminosity function for the early-type Pleiades stars appears to be bimodal—with only a few exceptions, we either detect these stars at fluxes in the range found for low-mass stars or we derive X-ray limits below the level found for most Pleiades dwarfs. The X-ray spectra for the early-type Pleiades stars detected by *ROSAT* are indistinguishable from the spectra of the low-mass Pleiades members. We believe that the simplest explanation for this behavior is that the early-type Pleiades stars are not themselves intrinsic X-ray sources and that the X-ray emission actually arises from low-mass companions to these stars.

Subject headings: open clusters and associations: individual (Pleiades) — stars: late-type — surveys — X-rays: stars

1. INTRODUCTION

The Pleiades is a natural target for observation with imaging X-ray telescopes because it is young enough that its low-mass members would be expected to be strong X-ray emitters, it is near enough (and has low enough H I column density) that reasonable X-ray count rates would be predicted, and it is compact enough that a significant fraction of the cluster can be imaged with a single exposure of a plausible X-ray telescope. As a result of these factors, the Pleiades was one of the primary open clusters observed with the imaging proportional counter (IPC) on the *Einstein* Observatory (Caillault & Helfand 1985; Micela et al. 1990). Micela et al. quoted nonblended detections for approximately 69 Pleiades members, and provided upper limits with typical sensitivities of order Log $L_X = 29.3$ ergs s^{-1} for a large number of other stars. An X-ray flare was detected from one of the low-mass Pleiades members according to Caillault and Helfand. The *ROSAT* all-sky survey has provided a second measure of the X-ray emission of Pleiades members, though with relatively poor sensitivity as the result of the low ecliptic latitude of the cluster. Schmitt et al. (1994) report the detection of 23 Pleiades members in a preliminary analysis of the survey data. One of the strongest sources identified in the *ROSAT* survey data was not detected by *Einstein*, probably due to an X-ray flare during the survey observations.

Because of its proximity and youth, the Pleiades has also been the subject of a considerable amount of effort in other wavelength regions. New proper motion membership studies have provided a more complete membership list for the cluster (Stauffer et al. 1991b; Prosser, Stauffer, & Kraft 1991; Rosvick, Mermilliod, & Mayor 1992; Klemola 1994). During the past decade, the Pleiades has served as a Rosetta stone for the study of the rotational velocity evolution of low-mass stars (van Leeuwen & Alphenaar 1982; Stauffer et al. 1984; Stauffer & Hartmann 1987; Soderblom et al. 1993). The Pleiades low-mass stars provide some of the most useful clues to puzzles

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ROSAT HRI OBSERVATIONS OF HOT STARS IN THE ORION NEBULA

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ABSTRACT

ROSAT HRI observations of hot (O6–A5) stars in the Orion Nebula region are presented. Fourteen of 21 O6–B5 stars were detected and all of them appear to have X-ray luminosities and L_x/L_{bol} ratios similar to field O6–B5 stars. The brightest star in the Trapezium, the O7 V star θ^1 C Ori, has notable variation in its X-ray emission; the variation seems to have the same phase dependence as recently found for the star's Hα emission. A maximum of six of 27 B6–A5 stars observed were detected; we argue that the most likely explanation for their X-ray emission is that it arises from unseen, low-mass binary companions.
Subject headings: ISM: individual (Orion Nebula) — stars: early-type — stars: individual (θ^1 Orionis C) — X-rays: stars

1. INTRODUCTION

X-ray emission has been detected with both the *Einstein* and *ROSAT Observatories* from stars throughout the H-R diagram (Vaiana et al. 1981; Helfand & Caillault 1982; Schmitt 1993), but there seems to be a dearth of single, main-sequence B6–A5 field stars that have been shown conclusively to emit X-rays (Grillo et al. 1992). In fact, most authors (e.g., Cassinelli 1985) have stated that only earlier and later type main-sequence stars are capable of emitting detectable X-rays; the handful of mid-A type star X-ray detections reported by Cash & Snow (1982) and Golub et al. (1983) are now believed to result from the X-ray emission of a late-type (K or M dwarf) main-sequence companion rather than of the A star itself (Schmitt et al. 1985).

This gap in the main-sequence X-ray luminosity function is expected from a theoretical point of view, since the mechanisms which allow for the production of X-ray emission in both earlier and later type stars are, most likely, incapable of operating in these main-sequence B6–A5 stars. The radiation-driven shocks in the models of Lucy & White (1980) and Lucy (1982) used to describe the X-ray emission in O and early B stars will never form in the B6–A5 stars since these stars are thought not to have sufficiently strong stellar winds, a primary requirement of these models. Likewise, approaching these B6–A5 stars from the cool end, one finds that the magnetic dynamo-heated coronal models (see, e.g., Rosner, Golub, & Vaiana 1985) used to explain the X-ray emission of later type stars (spectral types F–M) require an outer convection zone of sufficient depth for the dyamo to operate. Such surface convective regions do not exist in main-sequence B6–A5 stars. Hence, if a substantial flux of X-rays were to be observed from single stars in this spectral type range, a new emission mechanism would appear to be required.

A number of studies seem to show that X-ray emission from these types of stars is not as uncommon, though, if they are located in star-formation regions. In Walter et al.'s (1988) *Einstein* study of the Tau-Aur region one B9 star was detected; in Strom et al.'s (1990) *Einstein* study of the L1641 dark cloud another three were detected; and Schmitt et al. (1993) reported on *ROSAT* HRI detections of four late B stars in close visual binaries with T Tauri companions. In all of these cases, though, the possibility that the X-ray emission arises from a low-mass binary companion cannot be eliminated. Caillault & Zoonematkermani (1989; hereafter CZ) reported on the detection of a dozen X-ray emitting main-sequence B6–A3 stars in the Orion Nebula region using the *Einstein Observatory*. They considered the possibility that (1) these stars may not actually be the source of the X-rays, but that the emission may be attributable to T Tauri or "naked" T Tauri (NTT) star companions, since the two types of stars (B6–A3 and T Tauri) are similar in age and the T Tauri stars typically have an X-ray luminosity on the order of a few times 10^{30} ergs s^{-1}, similar to that of the sources that were found; or that (2) these hot stars are indeed the sources of the X-ray emission and that modifications to existing theories of stellar X-ray emission are required to explain the luminosities of these stars. Although a T Tauri or NTT companion would be a convenient explanation of the X-ray emission of B6–A3 stars in Orion, and such a proposition is allowed by the poorly determined binary statistics, there is no compelling evidence from other wavelength regimes or from the *Einstein* X-ray variability characteristics to support the contention that these stars are in binary systems.

CZ presented a statistical argument for the verity of these stars as the correct optical identifications of the X-ray sources; it was concluded that at least nine of the dozen X-ray sources must be correctly identified with B6–A3 stars (or to binary companions to those stars). However, it is likely that CZ were too conservative in the f_x/f_v cutoff for other possible candidates, i.e., they probably eliminated some viable late-type stellar candidates. A reanalysis of the entire *Einstein*/Orion database has been conducted by Gagné & Caillault (1994). They determine that eight of 85 B6–A5 stars are X-ray sources, agreeing with CZ's analysis in four cases. In addition to this inconsistent result, the large mean offset between the optical and X-ray positions (~36") found by CZ is disturbing, too.

There are two questions, then, which need to be resolved: (1) Are the X-ray sources centered on the positions of the Orion high-mass stars? and (2) if so, is the true source of the X-ray emission the high-mass star or does the X-ray emission orig-

2.