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Chandra Observations of the Pleiades Open Cluster: X-ray emission from late-B and A type Pleiades members

Kathryne J. Daniel[1,2], Jeffrey L. Linsky[1] , Marc Gagné[2]

Abstract. We present the analysis of 38.4 ks and 23.6 ks ACIS-I observations of the core of the Pleiades open cluster. Of the 101 sources detected in the $17' \times 17'$ region, 53 have not been cataloged at any other wavelength. Eighteen of 23 Pleiades members in the ACIS-I FOV were detected as X-ray sources with moderate to high time variability. Two of the early-type Pleiades members, HII 980 (B6 IV) and HII 956 (A7 V), are very bright X-ray sources, show soft X-ray spectra, and are variable with no obvious signs of flaring. K- and M-type cluster members with comparable X-ray luminosities have hard X-ray spectra and display strong flares. For non-flaring K- and M-type stars, L_X is 1–2 orders of magnitude lower. One A-type star, HII 1284 (A9 V), has X-ray properties comparable to these non-flaring K-type stars. One star, HII 1338 (F3 V), exhibits an X-ray flare and two others, HII 1362 (A7 V) and HII 1375 (A0 V) are not detected. Despite the low number statistics, this pattern among late-B to early-F stars suggests that some early-type stars like HII 980 and HII 956 are intrinsic X-ray emitters. Some, like HII 1284 and HII 1338, may have late-type companions and some, like HII 1362 and HII 1375, may be single, inactive stars. X-ray spectra and light curves of a larger sample of intermediate-mass stars are needed to confirm this trend.

1. Introduction

Current stellar theory predicts that stars with masses M$\geq 1.6 M_\odot$ have thin or nonexistent sub-photospheric convection zones. It is generally thought that the presence of a turbulent convective layer is necessary to drive a magnetic dynamo. It is this dynamo that creates the magnetic fields which heat the corona and are responsible for coronal X-ray emission. As a result, stars more massive than early-F stars are not expected to show dynamo-driven magnetic activity. Strong wind shocks on O- and early B-type stars lead to relatively soft, non-variable X-ray emission in very high-mass stars (Lucy & White 1980; Owocki, Castor, & Rybicki 1988; Owocki & Cohen 1999). Therefore, current models do not predict X-ray emission to arise from late-B to early-F type stars. However, Krishnamurthi et al. (2001), Huélamo et al. (2001), Stauffer et al. (1994), Caillault, Gagné, & Stauffer (1994), Berghöfer & Schmitt (1994), Schmitt et al. (1993), Micela et al. (1990), Pallavicini, Tagliaferri & Stella (1990), Caillault & Zootematkermani (1989), and Schmitt et al. (1985) have all recorded X-ray emission from a small percentage of the observed AB stars using the *Einstein* and ROSAT satellites. Golub et al. (1984), Caillault & Helfand (1985), Schmitt et al. (1993), Stauffer et al. (1994), Grillo et al. (1992), and Micela et al. (1996) have proposed that this X-ray emission from some early-type stars could be explained as emission from previously unknown late-type companions. In this study we use the X-ray emission characteristics of early- and late-type stars to explore the applicability of this model.

[1]JILA, University of Colorado

[2]Dept. of Geology & Astronomy, West Chester University

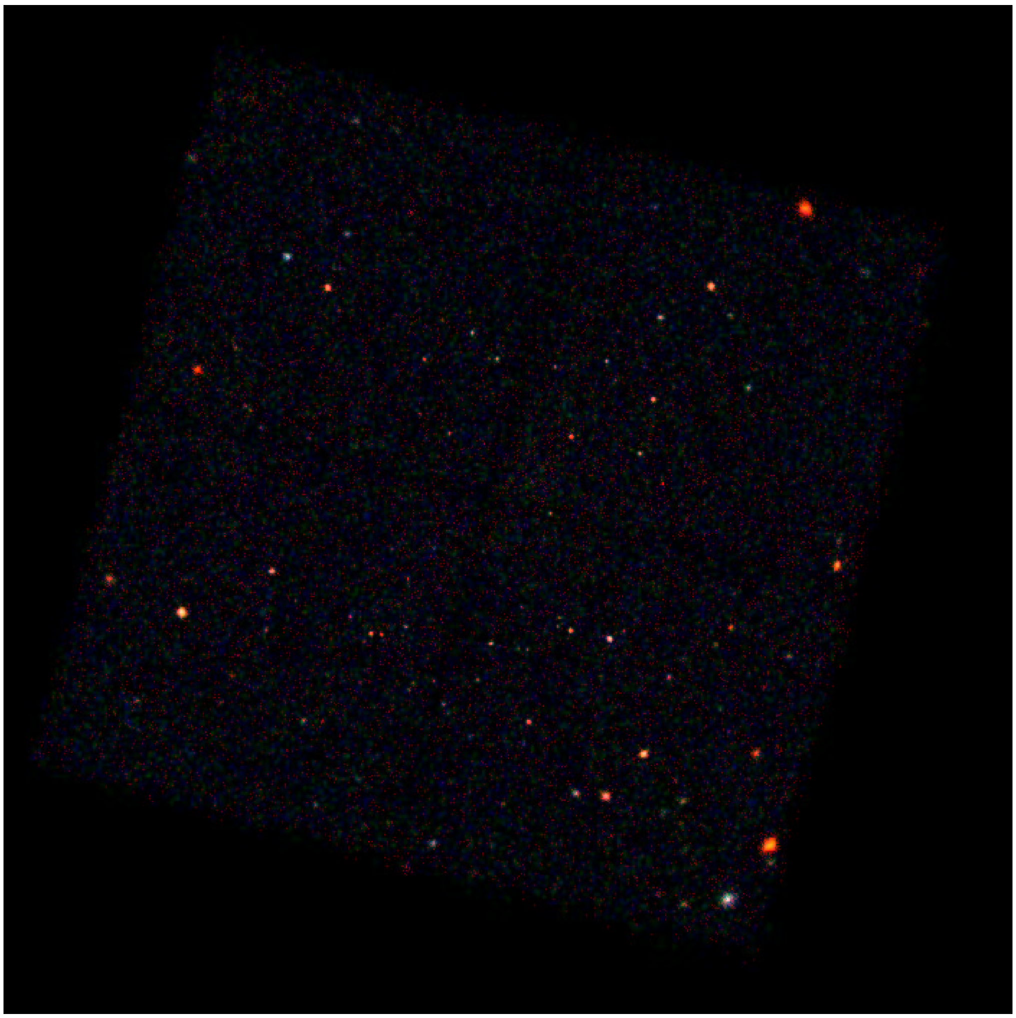

Figure 1. Coadded $17' \times 17'$ *Chandra* image generated from the ACIS-I data. This true-color image shows soft (0.5-1.0 keV), medium (1.0-2.0 keV), and hard (2.0-8.0 keV) energy counts as red, green and blue respectively.

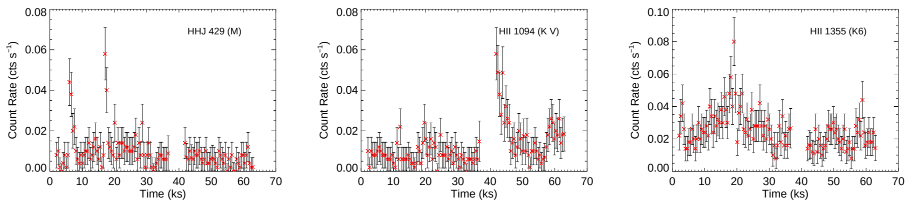

Figure 2. Representative X-ray light-curves of K-type stars detected by *Chandra*. All show the flare-like activity present on highly X-ray luminous late-type stars.

2. Observations

The *Chandra X-ray Observatory* (*Chandra*) observed the Pleiades open cluster core for a total of 56.4 ks. The data consist of 34.4 ks from September 18, 1999 (Krishnamurthi et al. 2001), and 21.0 ks from March 20, 2000.

3. Source Detections

Using coadded images and exposure maps we detected 101 *Chandra* sources by applying CIAO's wavelet-based algorithm tool, *wavdetect*. *Chandra* detected 18 of the 23 bona fide Pleiades members and all 5 of the possible members in the ACIS-I FOV (Pinfield et al. 2000; Belikov et al. 1998; Stauffer et al. 1998; Micela et al. 1996; Schilbach et al. 1995; and Hambly, Hawkins & Jameson 1993). In this paper, Pleiades membership is defined by stars with a proper motion probability (ppm) $> 50\%$. Possible members are stars with similar photometric properties as Pleiades members but where ppm$< 50\%$.

The range of spectral types detected by *Chandra* allows us to re-examine the question of whether B4-A7 type stars can intrinsically emit X-rays. No O-type or G-type Pleiades members are present in the *Chandra* FOV. As a consequence, we compare the early-type stars with K- and M-type Pleiades members.

4. X-ray Emission from late-B and A-type Stars

The hypothesis that late-B and A-type X-ray sources have late-type coronal companions is difficult to refute on the basis of X-ray luminosity or detection fraction alone. The AB-star X-ray luminosities are comparable to active G- and K-type stars and the fraction of X-ray emitting AB stars does not exceed the fraction of AB stars expected to have close late-type companions (Stauffer et al. 1994). With the increased signal-to-noise and wider bandpass of *Chandra*, we revisit the question of AB-star X-ray emission by comparing the hardness ratios, light curves, and X-ray spectra of AB X-ray sources with flaring and non-flaring K-type Pleiades members.

X-ray faint stars– The faint Pleiades X-ray sources in Table 1 are characterized by $\log L_{\rm X} < 28.20$ and $-0.20 <$ HR < 0.22. HII 1284's (A9 V) X-ray properties ($\log L_{\rm X} = 27.59$ and HR $= -0.20$) are consistent with X-ray emission from a late-type companion.

HII 956 (A7 V)– This non-flaring source is variable, has a high X-ray luminosity ($\log L_{\rm X} = 29.60$) and soft spectrum (HR$= -0.48$). The X-ray properties of HII 956 do not correspond to those of any K-type stars in this sample. The X-ray luminous K stars in our FOV are hard and show clear flare-like activity, unlike HII 956 (see Table 1). A comparison of the light-curves, in Figures 2-3, illustrates the

Table 1. Early- and late-type Pleiades members in the *Chandra* FOV

Name	ST	V	B−V	V−R	log L_X	HR[a]	K-S[b]	Variability
Non-Flaring K-type members:								
SRS 64425	K2 V	12.27	0.94	...	27.62	0.22	0.65	No
HHJ 92	...	19.52	...	0.92	28.09	-0.11	0.93	No
HCG 254	...	19.34	...	0.74	<27.17	...	...	...
Inactive Early-type members:								
HII 1375	A0 V	6.28	0.02	...	<27.17	...	...	...
HII 1362	A7 V	8.26	0.26	...	<27.17	...	...	...
HII 1284	A9 V	8.37	0.30	...	27.59	-0.20	0.53	No
Flaring K-type members:								
HII 1124	K3 V	12.32	0.98	0.49	29.33	-0.22	1.32	flaring
HII 1355	K6	14.02	1.40	0.97	29.54	-0.15	2.75	flaring
HII 1094	K V	14.02	1.40	...	29.23	-0.25	3.24	flaring
HII 930	K V	14.20	1.26	0.89	29.09	-0.19	1.59	flaring
HII 1061	K5 V	14.21	1.39	0.94	29.11	-0.21	1.70	flaring
HII 1280	K7.5 V	14.57	1.12	0.94	29.11	-0.28	1.84	flaring
Flaring M-type members:								
HHJ 429	M V	16.00	2.00	1.30	29.13	-0.11	2.53	flaring
HHJ 427	M V	16.10	...	0.90	28.55	-0.21	1.16	flaring
HHJ 299	M V	17.60	2.30	1.00	28.69	-0.10	1.91	flaring
MHO 8	M V	18.92	...	...	28.36	0.06	2.42	flaring
MHO 9	M V	19.02	...	...	27.98	-0.24	1.43	Yes
MHO 10	M	20.18	...	...	<27.17	...	...	...
MHO 11	M	21.44	...	...	<27.17	...	...	...
Active Early-type members:								
HII 980	B6 IVn	4.18	-0.06	-0.02	29.74	-0.34	1.91	Yes
HII 956	A7 V	7.96	0.32	...	29.60	-0.48	0.98	Yes
HII 1338	F3 V	8.69	0.46	...	28.92	-0.40	1.27	flaring
HII 1122	F4 V	9.29	0.46	...	29.51	-0.49	1.55	Yes

[a]The hardness ratio in the Pleiades is $\mathrm{H} = \frac{\mathrm{hard}-\mathrm{soft}}{\mathrm{hard}+\mathrm{soft}}$, where soft and hard bands are 0.5–1.0 keV and 1.0–8.0 keV, respectively.

[b]Cumulative Kolmogorov-Smirnov (K-S) statistic to a constant count-rate source. Short-term or flare-like variability typically corresponds to KS ≥ 1.0.

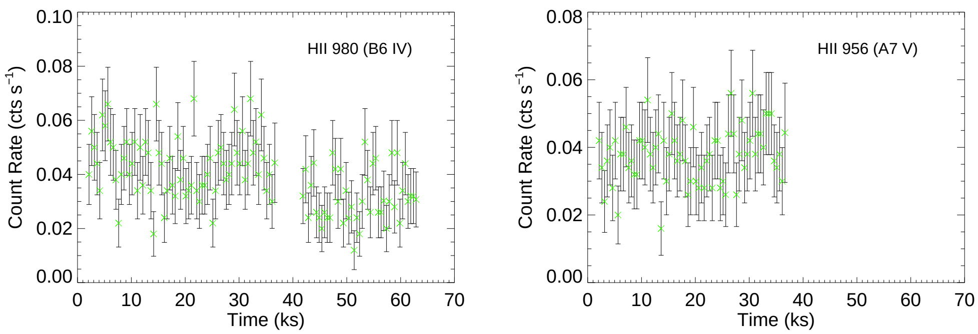

Figure 3. These light curves do not show the rapid rise and slower decay of flares seen on K-type stars of comparable X-ray luminosity (see Fig. 2). HII 980 and HII 956 show undulating, short-term variability over the course of a single observation, and larger variability from 1999 Sep 18 to 2000 Mar 20.

difference between the flare-like activity of active K stars and the rolling variability of HII 956. We suggest that HII 956 is an intrinsic X-ray emitter.

HII 980 (B6 IV)– This is the most X-ray luminous star in the *Chandra* FOV, with an X-ray luminosity of $\log L_X = 29.74$. Like HII 956, HII 980 does not have X-ray characteristics consistent with those of the active K stars. X-ray emission from HII 980 is softer (HR$= -0.34$) and does not exhibit the flare-like eruptions of the X-ray luminous K stars, but rather the undulating variability exemplified by HII 956 (see Figures 2-3). Since the X-ray emission is not consistent with the active K-type Pleiades members, we suggest that HII 980 is also an intrinsic X-ray emitter.

Undetected early-type stars– *Chandra* did not detect HII 1375 (A0 V) or HII 1362 (A7 V) with a very low upper limit of $\log L_X < 27.17$. As these stars have been repeatedly observed and not detected in the X-rays (Micela et al. 1999; Micela et al. 1996; Stauffer et al. 1994), we conclude that they are not intrinsic X-ray emitters and that they do not have G- or K-type companions.

5. Conclusions

This analysis of the coadded 56.4 ks ACIS-I image of the Pleiades Cluster core yields the following results:

1. We identified 101 X-ray sources, and extracted hardness ratios, Kolmogorov-Smirnov statistics, and count rates for each source. Among these were 18 of the 23 Pleiades members in the $17' \times 17'$ FOV.

2. We analyzed the X-ray properties of the 23 known Pleiades members. By comparing groups of early- and late-type Pleiades members we note the following trends associated with X-ray emission from early-type stars:

   (a) High L_X, soft spectra, and non-flaring light curves suggest that HII 980 (B6 IV) and HII 956 (A7 V) may be intrinsic X-ray emitters. If so, mechanisms for heating the coronae of such stars need further exploration.

   (b) HII 1284 (A9 V), and HII 1338 (F3 V) have X-ray properties comparable to those of K-type stars. In these cases the X-ray emission may come from an unseen K-type companion.

(c) Five Pleiades members are not detected in the combined Chandra image, putting stringent upper limits on the X-ray luminosity of some early- and late-type cluster members. These may be single, inactive stars.

Despite the small sample of Pleiades members in the *Chandra FOV*, a pattern among late-B to early-F stars does emerge: some early-type stars like HII 980 and HII 956 are intrinsic X-ray emitters. Some, like HII 1284 and HII 1338, may have late-type companions and others, like HII 1362 and HII 1375, may be single, inactive stars. X-ray spectra and light curves of a larger sample of intermediate-mass stars are needed to confirm this pattern. If confirmed, then new X-ray emission mechanisms, possibly related to large-scale magnetic fields, may be required.

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References

Belikov, A.N., Hirte, S., Meusinger, H., Piskunov, A. E., & Schilbach, E. 1998, A&A, 332, 575

Berghöfer, T.W., & Schmitt, J.H.M.M. 1994, ApJL, 292, 5

Caillault, J.-P., Gagné, M., & Stauffer, J.R. 1994, ApJ, 432, 386

Caillault, J.-P., & Zootematkermani, S. 1989, ApJ, 338, L57

Caillault, J.-P., & Helfand, D.J. 1985, ApJ, 289, 279

Grillo, F., Sciortino, S., Micela, G., Vaiana, G.S., & Harnden, F.R., Jr. 1992, ApJS, 81,795

Golub, J., Harnden, F.R., Maxson, C.W., Rosner, R., Vaiana, G.S., Cash, W., Jr., & Snow, T.P. 1984, ApJ, 278, 456

Hambly, N.C., Hawkins, M.R.S., & Jameson, R.F. 1993, A&AS, 100, 607 (HHJ)

Haro, G., Chavira, E., & Gonzalez, G. 1982, Bol. Obs. Tonantzintla Tacubaya, 3, 3 (HCG)

Hertzsprung, E.1947, Ann. Sternw. Leiden, 19, Part 1 (HII)

Huélamo, N., Brandner, W., Brown, A.G.A., Neuhäuser, R., & Zinnecker, H. 2001, A&A, 373, 657

Krishnamurthi, A., Reynolds, C. S., Linsky, J. L., Martín, E., & Gagné, M. 2001, ApJ, 121, 337

Lucy, L.B. & White R.L. 1980, ApJ, 241, 300

Micela, G., et al. 1999, A&A, 341, 751

Micela, G., Sciortino, S., Kashyap, V., Harnden, F.R., Jr., & Rosner, R. 1996, ApJS, 102, 75

Micela, G., Sciortino, S., Vaiana, G., Harnden, F.R., Jr., Rosner, R., & Schmitt, J.H.M.M. 1990, ApJ, 348, 557

Owocki, S.P. & Cohen, D.H. 1999, ApJ, 520, 833

Owocki, S.P, Castor, J.I., & Rybicki, G.B. 1988, ApJ, 335, 914

Pallavicini, R. , Tagliaferri, G., & Stella, L. 1990, A&A, 282, 403

Pinfield, D.J., Hodgkin, S.T., Jameson, R.F., Cossburn, M.R., Hambly, N.C., & Dervereux, N. 2000, MNRAS, 313, 347

Schilbach, E., Robichon, N., Souchay, J., & Guibert, J. 1995, A&A, 299, 696 (SRS)

Schmitt, J.H.M.M., Zinnecker, H., Cruddace, R., & Harnden, F.R., Jr. 1993, ApJ, 402, L13

Schmitt, J.H.M.M., Golub, L., Harnden, F.R., Jr., Maxson, C.W., Rosner, R., & Vaiana, G.S. 1985, ApJ, 290, 307

Stauffer, J.R., Schild, R., Barrado y Navascués, D., Backman, D.E., Angelova, A.M., Kirkpatrick, J.D., Hambly, N., & Vanzi, L. 1998, ApJ, 504, 805 (MHO)

Stauffer, J.R., Caillault, J.-P., Gagné, M., Prosser, C.F., & Hartmann, L.W. 1994, ApJS, 91, 625