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BURN OUT OR FADE AWAY? ON THE X-RAY AND MAGNETIC DEATH OF INTERMEDIATE MASS STARS

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ABSTRACT

The nature of the mechanisms apparently driving X-rays from intermediate mass stars lacking strong convection zones or massive winds remains poorly understood, and the possible role of hidden, lower mass close companions is still unclear. A 20 ks *Chandra* HRC-I observation of HR 4796A, an 8 Myr old main sequence A0 star devoid of close stellar companions, has been used to search for a signature or remnant of magnetic activity from the Herbig Ae phase. X-rays were not detected and the X-ray luminosity upper limit was $L_X \leqslant 1.3 \times 10^{27}$ erg s^{-1}. The result is discussed in the context of various scenarios for generating magnetic activity, including rotational shear and subsurface convection. A dynamo driven by natal differential rotation is unlikely to produce observable X rays, chiefly because of the difficulty in getting the dissipated energy up to the surface of the star. A subsurface convection layer produced by the ionization of helium could host a dynamo that should be effective throughout the main sequence but can only produce X-ray luminosities of the order 10^{25} erg s^{-1}. This luminosity lies only moderately below the current detection limit for Vega. Our study supports the idea that X-ray production in Herbig Ae/Be stars is linked largely to the accretion process rather than the properties of the underlying star, and that early A stars generally decline in X-ray luminosity at least 100,000 fold in only a few million years.

Key words: stars: activity – stars: coronae – stars: magnetic field – Sun: activity – Sun: corona – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The issue of whether late B- and early A-type stars are capable of generating and sustaining significant X-rays remains an outstanding problem in high energy stellar physics. The problem is relevant to both our understanding of the physics and structure of the stars themselves, and the evolution of their immediate environments.

There are two known ways non-accreting single stars are able to produce X-rays. In O and early B stars, shocks present in supersonic radiatively driven winds produce heating. Stars of type G and later, on the other hand, have thick convective envelopes with magnetic dynamo activity, much of whose energy is dissipated in the corona (e.g., Vaiana et al. 1981). Thick convective envelopes are absent above about 1.5 $M_\odot$, but thin surface convection layers present up to about type A5 appear to be enough to produce modest coronal heating and X ray emission (e.g., Robrade & Schmitt 2010; Günther et al. 2012). Between these two regimes lie the early A- and late B-type stars, which are insufficiently luminous to produce massive radiatively driven winds and also lack significant convection at the surface. Peculiar metal abundances are sometimes observed in these stars, "skin diseases" produced by various chemical separation phenomena at the surfaces, such as gravitational settling and radiative levitation, which in more active stars are smothered by mixing processes. This quietness also appears to manifest itself in X-ray quietness—indeed, various *ROSAT* searches for X-ray emission from normal A-type stars have found most to be X-ray dark down to limits of $L_X <$ a few 10^{27}–10^{28} erg s^{-1} (e.g., Simon et al. 1995; Schröder & Schmitt 2007), with significantly lower limits for nearby examples such as Vega. For this A0 V star, Pease et al. (2006) obtained $L_X < 3 \times 10^{25}$ erg s^{-1} from *Chandra* observations, corresponding to a bolometric fraction limit of $L_X/L_{\rm bol} < 9 \times 10^{-11}$ (see also Ayres 2008). The spectral type limit earlier than which A-stars begin to be plausibly X-ray dark, appears to be about A5 (e.g., Robrade & Schmitt 2010; Günther et al. 2012), corresponding to the spectral type of β Pictoris, from which Günther et al. (2012) recently confirmed the very weak X-ray emission tentatively identified by Hempel et al. (2005). Evidence is also building that the magnetic A and late B stars might maintain significant X-ray output (e.g., Drake 1998; Robrade & Schmitt 2011; Stelzer et al. 2011).

While it is tempting to declare the late B- and early A-type stars are essentially devoid of significant X-ray activity, a small fraction *are* seen in positional coincidence with bright X-ray sources. Schröder & Schmitt (2007) found that 342 A-type stars in the Bright Star Catalogue (Hoffleit & Jaschek 1991) can potentially be associated with X-ray sources found in *ROSAT* surveys, corresponding to a detection rate of 10%–15%. But what fraction of the X-ray detections are due to unseen late-type companions? In a sample of 11 late B-type main-sequence stars with resolved close companions at arcsecond separation—which is smaller than can be resolved by *ROSAT*—Stelzer et al. (2006) still found seven of the B stars to be coincident with the X-ray emission seen in *Chandra* observations capable of resolving the known components. More recently, De Rosa et al. (2011) found from an adaptive optics survey that B6–A7 stars coincident with an X-ray source are three times more likely to have close companions than a sample with no corresponding X-ray detections. This survey provides perhaps the strongest evidence to date that the source of the X-ray emission, at least in a sizable fraction of the sample, is the candidate companion.

One reason to suspect that at least some intermediate mass main-sequence stars are X-ray emitters is that pre-main sequence Herbig Ae/Be (HAeBe) stars—the intermediate mass nearly fully radiative counterparts to classical T Tauri stars—are routinely found to be coincident with X-ray sources with luminosities of a few 10^{31} erg s^{-1} down to about 10^{29} erg s^{-1} (Damiani et al. 1994; Zinnecker & Preibisch 1994; Hamaguchi et al. 2005; Stelzer et al. 2006, 2009; Hamidouche et al. 2008).

Stelzer et al. (2006) found an overall detection fraction of 76% for a sample of 17 HAeBes, and only half of these have known unresolved companions. They found that the observed X-ray emission cannot be explained by known companion stars in 35% of the sample. If the Herbig Ae/Be stars are indeed responsible for some of these detections, they are more vigorous sources than any true X-ray emitters among their more evolved main-sequence siblings. Stelzer et al. (2009) noted that if HAeBe X-rays are simply indicative of coronally active low-mass companions, their detection statistics imply a high fraction of higher order multiple systems among Herbig stars.

Since the limits to the X-ray luminosity of stars like Vega (A0 V), with an age likely in the range of about 100–500 Myr (Barrado y Navascues 1998; Hill et al. 2010; Yoon et al. 2010), are currently quite stringent at $L_X \lesssim 10^{25}\,\mathrm{erg\,s^{-1}}$, any X-ray emission it produced in a pre-main sequence star phase must have declined rapidly as it evolved to the main-sequence—by perhaps six orders of magnitude or more. Any X-ray activity of intermediate mass stars then occurs either particularly in the HAeBe phase and is related to the presence of disks, accretion, or associated jet-type activity, as appears to be the case for HD 163296 (e.g., Swartz et al. 2005; Günther & Schmitt 2009), or else represents magnetic dissipation and decays due to a limited non-thermal energy reservoir as originally proposed in the primordial rotational sheer dynamo model of Tout & Pringle (1995; see also Spruit 2002; Braithwaite 2006). Spectropolarimetric time series of Herbig Ae stars provide some support for the latter case, in revealing evidence for dipolar surface fields with polar magnetic field strengths of up to several hundred Gauss (e.g., Hubrig et al. 2014).

Arguably the most important aspect of any observational campaign hoping to resolve the question of X-ray activity in intermediate mass stars is to disentangle the role of companions. Studies of early A-type stars in whose single nature we have a high degree of confidence are therefore of special value. HR 4976A is one of these. It is a rare example of a nearby (72.8 ± 1.7 pc; van Leeuwen 2007) very young main-sequence A0 star, with an age estimated to be about 8 Myr. Here we report on *Chandra* observations of HR 4976A obtained to search for evidence of any remaining X-ray activity.

2. HR 4796A

HR 4976A rose to prominence following the discovery of its remnant dusty disk based on *Infrared Astronomical Satellite* data (Jura 1991), and through subsequent ground-based, near-IR imaging (Koerner et al. 1998; Jayawardhana et al. 1998). Its disk was later imaged at high spatial resolution by the *Hubble Space Telescope* (Schneider et al. 1999, 2009) and by ground-based adaptive optics (Thalmann et al. 2011). Imaging revealed signs of asymmetry and clearing that could be signatures of planetary mass perturbers (Wyatt et al. 1999; Schneider et al. 2009; Thalmann et al. 2011) but ruled out close stellar mass companions.

Of key importance to the question of its possible X-ray activity is the age of HR 4796A. A nearby M dwarf with the same proper motion is very likely a binary companion and enabled Stauffer et al. (1995) to assess the system age as 8 ± 2 Myr based on isochrone fitting and Li abundance. This estimate was revised to 10 Myr by Jura et al. (1998) based on the *Hipparcos* distance, and by Jayawardhana et al. (1998), who also incorporated more recent photometry and bolometric corrections and assessed 8 ± 3 Myr. Jayawardhana et al. (1998) noted that the isolated location of HR 4796, free from molecular clouds or substantial dust extinction, provides a lower age limit of a few Myr. Stauffer et al. (1995) based an upper limit to the age of 9–11 Myr on the strong Li absorption of HR 4796B.

Perhaps some caution should be applied to these age interpretations though. Tout et al. (1999) have shown that the accretion history of pre-main-sequence stars can affect their positions in the HR diagram, inducing potential age errors from isochrone fitting. The Li abundance can also be affected by accretion. Soderblom et al. (2013) also point out that published stellar model isochrones for young stars can be significantly different from one another. While HR 4976 has been identified as a member of the TW Hya association (TWA 11; Webb et al. 1999), whose age is often thought to be well-established at 8–10 Myr, Weinberger et al. (2013) have pointed out an apparent age spread of several Myr among association members. In light of such potential uncertainties, we allow conservatively the age of HR 4976 to be up to a factor of two higher than its nominal value, and adopt an age range of 5–16 Myr.

3. OBSERVATIONS AND ANALYSIS

Chandra observed HR 4796 using the HRC-I detector on 2006 December 2 with a net exposure of 20,800 ks. The HRC-I was preferred over ACIS because of its greater effective area at energies $E \lesssim 0.5$ keV, where a low-activity corona of cooler, more solar-like temperatures of $T \approx 2 \times 10^6$ K might show up.

We reduced the HRC-I data with CIAO 4.2 and applied detector pulse height-based background filtering.[4] Conservatively, this removes at most 5% of the source counts and we have included this correction in all the count rate and flux estimates below. The observation does not exhibit significant background flaring, and thus we did not apply additional time filtering.

The resulting X-ray image of the sky in the region around HR 4796 is illustrated in Figure 1. Close visual inspection of the data in the vicinity of HR 4796A revealed no tangible signs of an X-ray source, or of any events within 1″ of the stellar position. We therefore proceeded to obtain an estimate of the upper limit to the X-ray flux.

We defined a large rectangular region offset from the putative location of HR 4796A to measure the background, and found that the expected background under the source in a circular region of 1″ radius that encloses 97% of the point spread function (PSF), is 1.86 ± 0.07. Adopting the formulism of van Dyk et al. (2001), the nominal 68% credible range on the source intensity is $[0, 7.4 \times 10^{-5}]\,\mathrm{counts\,s^{-1}}$. However, because the source is undetected, we can also estimate the intensity that would be required for an unambiguous detection (see Kashyap et al. 2010): for a source to be detected at a significance of at least 99.7% (corresponding to a Gaussian-equivalent "3σ" detection with 7 counts) with a probability of 0.5, its intensity must be at least $2.8 \times 10^{-4}\,\mathrm{counts\,s^{-1}}$, and the lack of such a detection places this upper limit on the intensity of HR 4796A.

The count rate upper limit was converted to flux and luminosity upper limits by folding the response of the instrument with the radiative loss function for an isothermal plasma at temperatures in the range 10^5–10^7 K. For the latter, we adopted the APED radiative loss model (Smith et al. 2001) as implemented in the PINTofALE[5] IDL[6] software (Kashyap & Drake 2000) and assumed the solar abundance mixture of Grevesse & Sauval

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[4] http://cxc.harvard.edu/ciao/threads/hrci_bg_spectra/

[5] The Package for Interactive Analysis of Line Emission, freely available from http://hea-www.harvard.edu/PINTofALE/

[6] Interactive Data Language, Research Systems Inc.

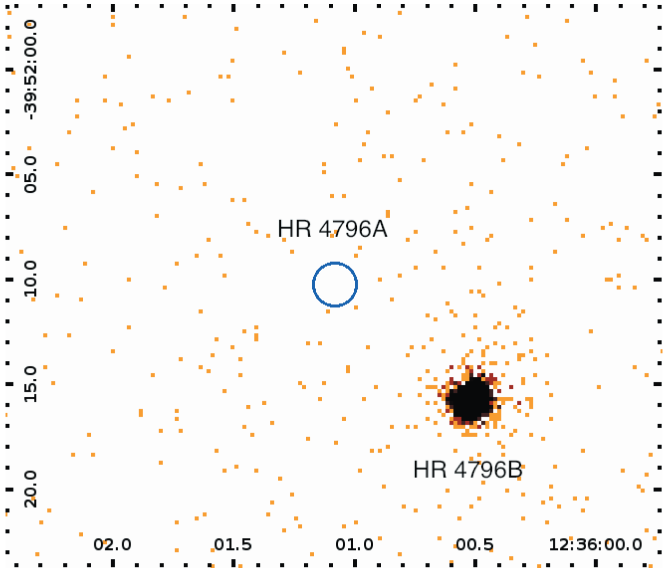

Figure 1. HRC-I image in the vicinity of HR 4796A from the 20.8 ks HRC-I observation (ObsID 7414) described here. The main target was not detected, with no events lying in a region of radius $1''$ centered on the position of the star. A large region was used to get an accurate assessment of the background with which to determine a count rate upper limit of 2.8×10^{-4} counts s^{-1}. The bright source to the southwest is HR 4796B, an M2.5V star used by Stauffer et al. (1995) to estimate an age of 8 ± 2 Myr for the system.

(A color version of this figure is available in the online journal.)

(1998). This X-ray flux and luminosity upper limit locus (assuming a distance of 73 pc) is illustrated, together with one computed with metal abundances reduced by a factor of ten, in Figure 2. It is difficult to know what the characteristic temperature of X-ray emission from HR 4796A might be, but since coronal temperatures in main-sequence stars with weak magnetic activity, such as the Sun, are generally about 1–2 $\times$ 10^6 K, for the ensuing discussion here we adopt the luminosity limit at $\log T = 6.3$, which is also independent of the assumed metallicity. The resulting X-ray luminosity for HR 4796A is $L_X \leqslant 1.3 \times 10^{27}$ erg s^{-1}, corresponding to an X-ray to bolometric luminosity ratio limit of $L_X/L_{\mathrm{bol}} \leqslant 1.9 \times 10^{-8}$ based on the bolometric luminosity of HR 4796A of $L_{\mathrm{bol}} = 18.1\ L_\odot$ (Koerner et al. 1998).

4. DISCUSSION

While our *Chandra* observations have only resulted in an upper limit to the X-ray luminosity of HR 4796A, it is of interest to place this limit in the context of possible mechanisms for generating X-rays in radiative stars.

There have been two different propositions explaining X-ray activity of HAeBe stars and its evident precipitate decline. The first is that magnetic activity depends on star-disk interactions and, perhaps, associated jet activity (see, e.g., Günther & Schmitt 2009); once the accreting gas disk is sufficiently dissipated the magnetic activity is curtailed (Hamaguchi et al. 2005). The second is the gradual dissipation by means of some magnetic dynamo of primordial rotational shear that remains between the surface and deeper layers of the star from its initial collapse (Vigneron et al. 1990; Tout & Pringle 1995; Spruit 2002). We consider the latter below, together with two other potential mechanisms of X-ray generation: the decay of a magnetic field left over from formation, and a subsurface convection zone thought to exist in late B-type and early A-type stars.

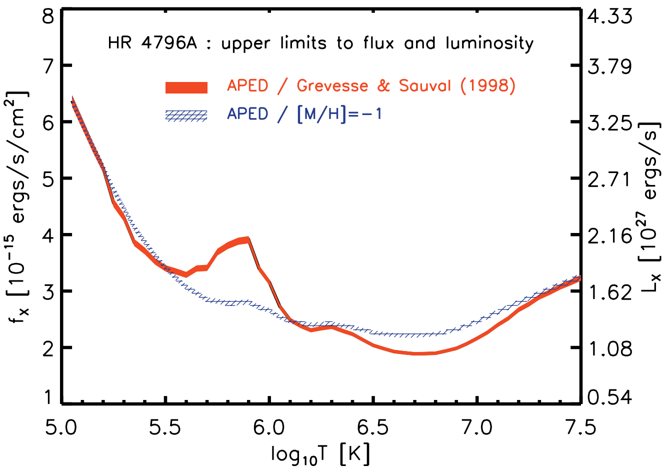

Figure 2. Relationship between source count rate and X-ray flux and luminosity as a function of temperature for HR 4796A for the distance of 73 pc. Curves were computed using the APED optically thin plasma radiative loss model. Here we adopt the luminosity limit at $\log T = 6.3$, $L_X \leqslant 1.3 \times 10^{27}$ erg s^{-1}, which is also independent of the assumed metallicity.

(A color version of this figure is available in the online journal.)

4.1. X-rays from a Shear Dynamo

In this section we describe two mechanisms that tap the energy in the primordial differential rotation and potentially result in X-ray emission. Both are dynamos consisting of two steps: first, any seed magnetic field present in the star will be wound up by the differential rotation to become a predominantly toroidal field. Then, to close the dynamo loop, it is necessary to convert some of this toroidal component back into the poloidal field, which can then be wound up again. In convective dynamos, this conversion from the toroidal into the poloidal field is achieved by convective motion; in a radiative zone some magnetic instability can be used. Tout & Pringle (1995) developed a dynamo model in which the toroidal-into-poloidal conversion works via the Parker (magnetic buoyancy; Parker 1966) instability. Spruit (2002) and Braithwaite (2006) developed a similar idea, although in more physical detail and based on a different instability, the so-called Tayler instability (Tayler 1973). As we shall see, the two different treatments result in very different timescales for dissipation of shear energy, although there are large uncertainties in both.

The relations of Malkov (2007) indicate a mass of 2.6 $M_\odot$ for spectral type A0. Following Equation (2.6) of Tout & Pringle (1995), the available shear energy for a star of this mass could be as high as 7×10^{47} erg, and, as those authors pointed out, sufficient to power a typical X-ray luminosity of HAeBe stars for the stellar lifetime, even with a conversion efficiency of a percent or less. While the parameters are somewhat uncertain, Tout & Pringle (1995) found the initial rotational shear, $\Delta\Omega_0$, to decline with time, t, according to

$$\Delta\Omega = \frac{\Delta\Omega_0}{(1 + t/\tau)}, \qquad (1)$$

where τ is the decay timescale (t_0 in the Tout & Pringle 1995 nomenclature), and the initial X-ray luminosity, L_{X_0}, to decay in time as

$$L_X = \frac{L_{X_0}}{(1 + t/\tau)^3}. \qquad (2)$$

Tout & Pringle (1995) found $\tau \sim 10^6$ yr, based on reasonable guesses of relevant parameters. This also corresponds to the timescale of evolution of HAeBe stars and the typical time over which they appear X-ray bright (e.g., Hamaguchi et al. 2005). The parameter describing the efficiency of field generation on which the timescale τ depends to the inverse third power lacks empirical constraints, however. Since its value can only be considered to be an order of magnitude estimate, the decay timescale should also be considered very uncertain, by perhaps up to a factor of a thousand or so.

Spruit (2002; see also Spruit 1999; Braithwaite 2006) noted that the Tayler instability (Tayler 1973) is likely to be more relevant for a stably stratified star than the Parker instability, since it sets in at much lower magnetic field strengths. This is an interchange instability of toroidal fields, similar to the pinch instability in plasma physics. The instability necessarily involves some movement in the radial direction, and so has to work against the stable stratification. In the case where the composition gradients are insignificant (as in young stars), thermal diffusion can facilitate radial motions by reducing the effect of the stratification. In this regime, Spruit obtained an expression (Equation (29) of Spruit 2002) of the following type for the azimuthal stress due to the field generated by the dynamo for the case of negligible compositional gradient,

$$S \approx \frac{B_r B_\phi}{4\pi} = \Lambda \Omega^{3/2} \Delta\Omega, \tag{3}$$

where Ω is the rotation rate of the layers under consideration. Here we have included general terms related to the structure of the star in question into a parameter Λ, and for simplicity of comparison have adopted the nomenclature of Tout & Pringle (1995) in which $\Delta\Omega$ is the change in angular velocity over the region of the star in which the dynamo is expected to operate. This shear is continually eroded by the azimuthal stress and we can write

$$\frac{d(\Delta\Omega)}{dt} \propto \Omega^{3/2}\Delta\Omega. \tag{4}$$

The decay of shear is then likely to depend on whether significant angular momentum is lost and the average rotation rate in the dynamo region declines with time, or angular momentum is conserved and the average rotation rate can be approximated as being constant. During the HAeBe phase, in which angular momentum can be dissipated by a wind, and assuming $\Delta\Omega \propto \Omega$, Equation (4) leads to the solution

$$\Delta\Omega = \frac{\Delta\Omega_0}{(1 + t/\tau)^{2/3}}, \tag{5}$$

where the timescale τ is the decay timescale, as before; the time taken for the shear to drop to half its original value is 1.8τ.

For an early A-type star lacking a strong wind and significant magnetic braking, the total angular momentum should remain approximately constant. If we assume in this case that the mean rotation velocity of the dynamo layers is relatively unchanged by the dissipation of shear, and Ω is approximately constant, the solution to Equation (4) is simply $\Delta\Omega = \Delta\Omega_0 \exp(-t/\tau)$, where $\Delta\Omega_0$ is the initial rotational shear and τ is the timescale for its decay. This time dependence differs from that of Tout & Pringle (1995; Equation (3.13)) and Equation (1) here, who obtained a $1/t$ rather than exponential decay.

In order to understand the time dependence of surface X-ray emission for a Tayler–Spruit dynamo, we would need to know the rate at which the magnetic field is brought to the surface. Mullan & MacDonald (2005) argued that the Tayler and buoyancy instabilities are not mutually exclusive and that fields generated on the basis of the Tayler instability can be brought to the surface by magnetic buoyancy; we return to this further later. Here, while the following approach is somewhat arbitrary, for the sake of comparison with the Tout & Pringle (1995) result we apply the same arguments used by them to estimate surface X-ray activity.

We assume that some fraction, ε, of the magnetic field arriving at the surface by upward buoyant drift is scavenged off eventually to be dissipated in the form of X-rays. In analogy with Tout & Pringle (1992), the X-ray luminosity is then

$$L_X \approx \varepsilon \frac{4}{3}\pi R^3 \frac{d}{dt}\frac{B^2}{8\pi}, \tag{6}$$

where R is the stellar radius. Tout & Pringle (1992) assumed that magnetic flux escapes at a speed $\sim 0.1 v_A$, where v_A is the average Alfvén speed. For $v_A = B/\sqrt{4\pi\rho}$ and a timescale for the emergence of field of $R/0.1v_A$, we can write

$$L_X \approx \varepsilon \frac{4}{3}\pi R^3 \frac{B^2}{8\pi}\frac{0.1 v_A}{R} \approx \frac{0.1\varepsilon R^2}{12(\pi\rho)^{1/2}} B^3. \tag{7}$$

Since all the terms except for B in Equation (7) are constants for a given star, the X-ray luminosity then scales as the cube of the mean magnetic field. Spruit (2002) finds that the azimuthal field should be much larger than the radial field, and we can ignore the latter in considering both the magnetic energy and Alfvén speed. From Equation (22) of Spruit (2002), the azimuthal field depends only on the rotation rate, the differential rotation, and quantities that are constants for a given star, $B_\phi \propto \Delta\Omega^{1/2}\Omega^{5/8}$. If the average rotation velocity remains approximately constant for the main-sequence phase, the X-ray luminosity is expected to scale as

$$L_X \propto \Delta\Omega^{3/2}\Omega^{15/8} \propto \Delta\Omega^{3/2}. \tag{8}$$

Combining this with the solution to Equation (4), the time dependence of the X-ray luminosity is then

$$L_X(t) = L_{X_0} \exp\left(-\frac{3t}{2\tau}\right). \tag{9}$$

It would now be useful to estimate the timescale of the decay. From Spruit (2002; Equation (32)), one can express the shear stress in terms of an effective viscosity, which is given by $\nu \sim r^2\Omega(\Omega/N)^{1/2}(\kappa/r^2N)^{1/2}$, where κ is the thermal diffusivity, N is the buoyancy frequency, and r the radial coordinate. The timescale τ for the dissipation of the energy decaying as $E_{dr} = E_{dr}(t = 0)\exp(-t/\tau)$ is then given by

$$\tau \sim \frac{r^2}{\nu} \sim \Omega^{-1}\left(\frac{N}{\Omega}\right)^{1/2}\left(\frac{R^2N}{\kappa}\right)^{1/2}, \tag{10}$$

$$\sim \frac{P_{\rm rot}^{3/2}\tau_{\rm KH}^{1/2}}{P_{\rm bu}}, \tag{11}$$

where $N \sim \Omega$ close to the break-up velocity, $P_{\rm rot}$ and $P_{\rm bu}$ are the spin period and break-up spin period, respectively, and $\tau_{\rm KH}$ is the Kelvin–Helmholtz timescale. A 2.6 $M_\odot$ star has $\tau_{\rm KH} \sim 2 \times 10^6$ years and $P_{\rm bu} \sim 5$ hr, so with a rotation period of 1 day we would have a decay timescale of 300 years. Thus, for this formalism, the differential rotation is probably damped too quickly to see X-rays by the time the star becomes observable. However, this timescale assumes that the dynamo is at saturation, whereas in reality it may take rather longer than this timescale just to reach saturation. This should, in any case, happen faster than $\tau_{\rm KH}$, so this mechanism should dissipate shear energy on a timescale shorter than the thermal timescale on which pre-MS stars evolve (see Braithwaite & Spruit 2014). Consequently, we can expect it to work continuously and efficiently as the convective envelope retreats outward and to keep the radiative zones in approximately solid-body rotation at all times. In this picture, it dissipates the shear energy present in the convective zones at a rate at least a couple of orders of magnitude smaller than the luminosity of the pre-MS star.

Since the dynamo field strength tends to zero toward the surface, in order to dissipate some of the magnetic energy in the X-ray emission it is necessary to bring stronger fields from further down upward to the surface. This ultimately determines the efficiency with which the differential-rotation energy is converted to X-rays. Bringing the field to the surface is difficult because it has to be brought from deep in the envelope, where diffusive buoyancy acts slowly (see, e.g., MacGregor & Cassinelli 2003). As we noted and employed above, Tout & Pringle (1995) assumed a buoyancy turnover velocity of $0.1v_A$. Mullan & MacDonald (2005) looked at differentially rotating radiative stars with the Tayler–Spruit mechanism and found that the fields produced can be brought to the surface by buoyancy instability, which operates on a dynamic timescale. They find that field strengths of order 100 G are possible at the surface. Such a field strength is compatible with spectropolarimetric observations of Herbig Ae stars that find dipole-like fields with polar field strengths of up to a few hundred Gauss (e.g., Hubrig et al. 2014). The energy dissipation rate is more difficult to calculate, since it depends on the timescale and frequency with which magnetic features are brought upwards, but we can estimate this timescale as simply the Alfvén timescale for fields of this strength, which is $\sim$1 yr. This gives a rate of energy deposition through the photosphere of around 10^{28} erg s^{-1}, but, as noted above, this would be expected to die away on a rather short timescale.

This scenario is, then, much more pessimistic for the detection of X-rays on the early main sequence than the Tout & Pringle (1995) picture, although the large uncertainties in both methods for estimating the decay timescale cannot be overemphasized.

4.2. *Decay of Primordial Magnetic Fields*

According to the failed fossil theory (Braithwaite & Cantiello 2013), radiative stars can host weak magnetic fields in continuous dynamic evolution. The star could inherit a field from the parent cloud from which it formed or a field could be left behind by a pre-main-sequence convective dynamo. Either way, when the star is formed, its magnetic field is not in MHD equilibrium, and evolves on its own dynamic timescale. As it does so, magnetic energy is lost and the field strength drops. While in the strongly magnetic Ap stars an equilibrium is quickly reached and the field essentially stops evolving (a fossil field), a so-called *failed fossil* field is still evolving on a timescale given in terms of the Alfvén timescale and rotation rate by $\tau_{\rm A}^2\Omega$, which is then equal to the age of the star t. E is the magnetic energy in the star and can be expressed in terms of an average field strength as $E \sim (4\pi/3)R^3B^2/8\pi$. If M is the mass of the star and L is the characteristic length scale of the magnetic field, the Alfvén timescale is $\tau_{\rm A} = L/v_{\rm A} = L\sqrt{4\pi\rho}/B$, where the mean density $\rho = M/(4\pi/3)R^3$. Putting these together, we find that the magnetic energy falls at a rate

$$\dot{E} \sim -\frac{ML^2\Omega}{2t^2}. \tag{12}$$

Some fraction, ζ, of this energy will be dissipated at and above the stellar surface and give rise to X-ray emission. However, putting in the numbers we have:

$$L_{\rm X} = -\zeta\frac{dE}{dt} \sim 4\times 10^{23}\,\zeta\left(\frac{M}{M_\odot}\right)\left(\frac{L}{R}\right)^2 \times\left(\frac{P}{\rm day}\right)^{-1}\left(\frac{t}{\rm Myr}\right)^{-2}\,{\rm erg\,s^{-1}}. \tag{13}$$

Clearly, magnetic fields of this kind are unlikely to produce observable X-ray emission, even in very young main-sequence stars.

In pre-main-sequence stars, the situation is rather different. In general, any strong magnetic field present in a convective star is quickly brought to the surface by its own buoyancy (Braithwaite 2012), where presumably a significant fraction of its energy is dissipated in a hot corona. However, this buoyant expulsion happens on a short timescale, so that in accreting protostars the result of the buoyancy is more likely to be the prevention of flux accretion. The X-ray flux from the dissipation of magnetic energy would then be indistinguishable from that from the accretion itself, except in certain circumstances when spectroscopic signatures of accretion shocks might be observed (e.g., Kastner et al. 2002; Stelzer & Schmitt 2004; Drake 2005; Günther et al. 2006; Brickhouse et al. 2010). A convective dynamo would then be responsible for X-rays seen after accretion has ceased.

4.3. *Subsurface Convection*

More promising for the production of X-rays are subsurface convective layers (Cantiello & Braithwaite 2011; Cantiello et al. in preparation). These layers, which owe their existence to opacity bumps from the ionization of iron (in O and late-B stars) and helium (in late-B and early-A stars), lie just below the stellar surface, in contrast to the photospheric convection in stars later than about A5.

Hosting a dynamo, the subsurface convection in early-A and late-B stars produces a magnetic field. It is worth noting, however, that the convection in these layers transports a fraction of only about 10^{-3} of the stellar luminosity, so that the magnetic energy production will be correspondingly lower than that produced by the strong convection in a solar-type star. In any case, the magnetic field produced easily floats upward through the overlying radiative layer. This works essentially because the magnetic field produces pressure without mass; magnetic features are in total pressure equilibrium with their surroundings and therefore have a lower gas pressure. Heat diffuses efficiently into them and so they maintain the same temperature as their surrounding, have a lower density, and rise. This buoyant rise is limited by aerodynamic drag and takes place at the Alfvén speed. Once the magnetic field crosses into the low-density environment above the photosphere, its energy is dissipated. In solar-type and low-mass stars we see that X-ray emission is correlated with rotation speed up to a certain saturation level (e.g., Pizzolato et al. 2003; Wright et al. 2011), when the Rossby number (defined as $P_{\rm rot}/\tau_{\rm conv}$) is around 0.1; at Rossby numbers below this the X-ray emission $L_{\rm X}$ accounts

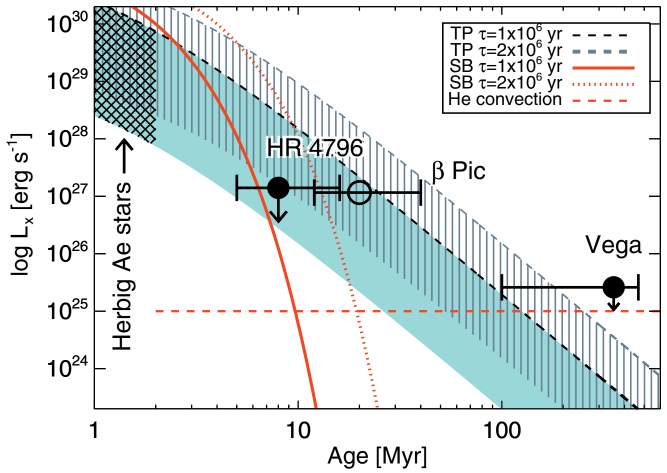

Figure 3. X-ray luminosity vs. time for shear dynamo models compared with observations of single A-type stars. The hashed region to the left represents the range of X-ray luminosities of Herbig Ae stars. The dashed curves correspond to a natal X-ray luminosity of $L_{X_0} = 2 \times 10^{31}$ erg s^{-1} and two different values for the rotation shear decay timescale for the Tout & Pringle (1995, TP) model. The solid and dotted curves correspond to an exponential X-ray luminosity decay that we infer from the rotational shear dissipation found by Spruit (2002, SB; see also Braithwaite 2006) assuming the Tout & Pringle (1995) prescription for magnetic flux rising due to buoyancy. The horizontal dashed curve corresponds to our estimate of a base level X-ray luminosity due to a weak sub-surface convection zone. The β Pic detection of Günther et al. (2012) is shown with a hollow symbol because its X-ray emission likely originates from a thin surface convection zone.

(A color version of this figure is available in the online journal.)

for a fraction of around 10^{-3} of the total luminosity $L_{\rm bol}$. The convective turnover time in an A0 star should be a few hours, so the Rossby number in a fast rotator will be $\geqslant$3, which in solar-type stars would give $L_{\rm X}/L_{\rm bol} \approx 10^{-6}$. Obviously it is little better than speculation that a thin-layer dynamo would work in the same way in this respect, as a dynamo operating throughout a convective envelope, but assuming it does, we have

$$L_{\rm X} \sim 10^{25} \left(\frac{P}{12\ {\rm hr}}\right)^{-2} {\rm erg\ s}^{-1} \qquad (14)$$

for a 2 $M_\odot$ star with $L = 25\ L_\odot$, taking the approximate power of -2 on the period from Pizzolato et al. (2003), taking into account the aforementioned convective transport fraction of 10^{-3}, and assuming an efficiency of 0.1 in getting the magnetic energy through the overlying radiative layer, a rough estimate that comes from the density ratio (and consequent magnetic field strength ratio) across the radiative layer.

4.4. Confronting Theory and Observations

The X-ray luminosity upper limit we obtained for HR 4796A is illustrated, together with that of Vega, in the context of the X-ray production mechanisms discussed in Sections 4.1–4.3 in Figure 3. A similar figure was presented by Pease et al. (2006) based on the stringent upper limit obtained for the X-ray luminosity of Vega. Since that time, an analysis by Yoon et al. (2010) of high-resolution spectra, visible/near-IR fluxes, and optical interferometry suggest that Vega is significantly less massive and older than had been thought, with an age of 454 ± 13 Myr, instead of the 200 ± 100 Myr estimate based on kinematic similarity with, and assumed membership of, the Castor moving group (Barrado y Navascues 1998). A greater age for Vega would imply a less stringent constraint on shear and failed fossil dynamo mechanisms, but at the same time emphasizes the value of HR 4796A as a constraint at young ages.

The hashed region to the left in Figure 3 represents the observed range of X-ray luminosity of Herbig Ae stars, and the shaded continuation to the right that might be expected of main-sequence early A-type stars for rotational shear decay timescales of 10^6 and 2×10^6 yr. They are bounded by initial X-ray luminosities $L_{X_0} = 2 \times 10^{29}$–$2 \times 10^{31}$ erg s^{-1}, which match the approximate luminosity range of Herbig AeBe stars (e.g., Damiani et al. 1994; Zinnecker & Preibisch 1994; Hamaguchi et al. 2005; Stelzer et al. 2006).

Skinner et al. (2004) used the Tout & Pringle (1995) formula to predict the present-day L_X of the closest known HAeBe star, HD 104237: while the estimate appears too high by a factor of about 4–20, within the uncertainties in the age and spectral type of HD 104237 the disagreement is perhaps not unreasonable as Skinner et al. (2004) note. Observations of typical HAeBe stars provide some additional calibration: Hamaguchi et al. (2005) found evidence that the age of X-ray activity decay is 10^6 yr. At an age of >100 Myr and assuming the decay law remains applicable to greater ages, the X-ray luminosity of Vega is then expected to have decayed by seven orders of magnitude to an unobservable 10^{24} erg cm^{-2} s^{-1} or so, in agreement with current limits (Pease et al. 2006). In contrast, very young, early type-A stars at ages of about 10 Myr should have declined in L_X by factors of 10^3–10^4.

For an A0 star of mass 2.6 $M_\odot$, the Tout–Pringle initial X-ray luminosity is $L_{X_0} \approx 10^{31}$ erg s^{-1}, or close to the case of the loci in Figure 3. At face value, our observed limit for HR 4976A weakly excludes the Tout & Pringle (1995) model, but is more consistent with our Spruit (2002)-based formula assuming, probably optimistically, that magnetic field is brought efficiently to the surface by magnetic buoyancy. However, as we have noted, both theoretical approaches involve significant uncertainty. As Tout & Pringle (1995) admit, their formulism includes some parameters with values that cannot be precisely defined or determined. These include some physical aspects of the model that might be expected to be the same for all stars, such as the efficiency of conversion of magnetic flux into observable X-rays, and a star-specific parameter describing the natal rotational shear. Within the Tout–Pringle framework, the observed spread in X-ray emission for stars at a given age and similar mass must in fact derive from the natal differential rotation.

The observed rotation speed of HR 4796A is $v \sin i = 152$ km s^{-1} (Royer et al. 2002), the radius is 1.6 $R_\odot$ (Rhee et al. 2007), and the disk inclination is 76° (Schneider et al. 2009; Thalmann et al. 2011). If the stellar and disk inclinations are the same, the stellar equatorial velocity is 157 km s^{-1} and the rotation period is about 0.5 days. In relation to the extensive sample of rotation velocities of Zorec & Royer (2012), HR 4796A lies near the middle of the distribution for stars with masses 2.4–3.85 $M_\odot$ and is rotationally typical. In the presence of a shear-related spread in a Tout–Pringle type model, and not knowing what rotational shear, if any, remains in HR 4796A, our X-ray luminosity limit is only able to rule out shear dynamo decay timescales $\tau \gtrsim 2 \times 10^6$ yr.

A fairly short timescale for dissipation of natal rotational shear is consistent with stellar rotation observations. From an extensive survey of stellar rotation rates, Zorec & Royer (2012) have shown that the distribution of surface rotation periods for early-A stars evolves only very slowly, over a large fraction of the main sequence lifetime. Since these stars are not expected to be spun down or up by any mass loss, the surface rotation velocity change is probably due to redistribution of angular momentum within the star. The implication is that large natal shear has already been dissipated in these stars, and subsequent surface rotation evolution is due to the gradual decline of the residual shear. A shear dynamo dissipates differential rotation, and the timescale over which this occurs is empirically limited by the shear energy available to power the observed X-rays. Tout & Pringle (1995) assumed a conversion efficiency of 10^{-3} for a timescale of $\sim 10^6$ yr. A longer timescale could be achieved assuming a greater conversion efficiency, but in addition to potential physical difficulties with a high efficiency of energy conversion, longer timescales of decay would not match either the slow evolution of surface rotation of most main-sequence A stars or the observed plunge into X-ray darkness of early A stars following the pre-main sequence phase.

Difficulties facing shear-driven dynamo mechanisms of X-ray emission include recent theoretical work by Arlt & Rüdiger (2011), who found only very weak dynamo action from numerical simulations of a three-dimensional spherical shell with differential rotation, and potential difficulties in getting any dynamo-generated field to the stellar surface (e.g., Braithwaite & Cantiello 2013). Hamaguchi et al. (2005) suggest that X-ray activity is associated with accretion and jet activity, since the X-ray decline in Herbig Ae stars seems to accompany the dissipation of the accreting gas disk.

The X-ray luminosity we predict from a subsurface He convection zone in late B- and early A-type stars lies below our current upper limit for Vega by a factor of 2–3, but carries a large uncertainty. Thus, the lack of an X-ray detection of Vega does provide some constraints to such a dynamo. Pushing the X-ray detection limit significantly lower for Vega-like stars would be of considerable interest for investigating this further.

Detectable main sequence X-ray emission does appear to switch on at masses only slightly below that of Vega and HR 4796A. Tantalizing evidence that young mid-A type stars can have residual X-ray activity came from the *FUSE* detection of transition region lines in the spectrum of the 12 Myr old A6 V star β Pic (Bouret et al. 2002). A tentative detection of the O VII emission was subsequently made from XMM-Newton observations, indicating a plasma temperature of 6×10^5 K (Hempel et al. 2005). It was speculated that β Pic either has a cool corona or a boundary layer between the photosphere and its remnant disk (Hempel et al. 2005). A deep *Chandra* observation of β Pic by Günther et al. (2012) has succeeded in detecting the star with $L_X = 1.3 \times 10^{27}\,\mathrm{erg\,s^{-1}}$ in the 0.06–2 keV band. The emission is consistent with that expected from an optically thin plasma, and Günther et al. (2012) concluded the origin is coronal X-rays. This makes β Pic the hottest coronally active star detected so far. β Pic is also illustrated in Figure 3 and its position suggests the X-rays could originate from a shear dynamo. However, fairly cool (3×10^6 K) coronae have also been detected on the planet-bearing A5 V star HR 8799 (aged about 60 Myr; Robrade & Schmitt 2010) and on Altair (A7 IV-V; aged 1.2 Gyr; Robrade & Schmitt 2009). All three of these stars are near the boundary of both observational and theoretical temperature limits of significant photospheric convection on A-type stars, and above which significant convection is not expected or observed (e.g., Landstreet et al. 2009; Kupka et al. 2009). The β Pic, HR 8799, and Altair coronae then most likely originate from a convection-driven, rather than shear-driven dynamo.

5. SUMMARY

We have investigated the plight of X-ray emission in intermediate mass stars immediately following the Herbig Ae phase. A *Chandra* HRC-I observation of HR 4796A, an 8 Myr old main sequence A0 star devoid of close stellar companions, failed to detect the star, giving an upper limit to the X-ray luminosity of $1.3 \times 10^{27}\,\mathrm{erg\,s^{-1}}$. This limit is still weakly consistent with predictions for dynamos driven by rotational shear and for an optimistic scenario of magnetic flux brought efficiently to the surface by magnetic buoyancy. However, examining possible sources of X-rays from such stars in more detail, we find that tapping the large kinetic energy present in the star, initially in the form of differential rotation, is unlikely to produce observable X-rays, chiefly because of the difficulty in getting the dissipated energy up to the surface of the star. More promising is a subsurface convection layer produced by the ionization of helium, which could host a dynamo. This mechanism, which should be effective throughout the main-sequence, could produce X-ray luminosities of order $10^{25}\,\mathrm{erg\,s^{-1}}$—only moderately below the current detection limit for Vega. It looks likely therefore that X-ray production in Herbig Ae/Be stars is linked to the accretion process, rather than the properties of the star itself.

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