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OPTICAL AND INFRARED EMISSION FROM THE ANOMALOUS X-RAY PULSARS AND SOFT GAMMA-RAY REPEATERS

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ABSTRACT

We show that the irradiated accretion disk model can account for all the optical and infrared observations of the anomalous X-ray pulsars in the persistent state. While placing an upper limit on the inner disk radii, and thus on the strength of the dipole component of the stellar magnetic field, the model fits do not constrain the outer disk radii. And while magnetar fields ($B_* > 10^{14}$ G) in higher multipoles are compatible with the irradiated disk model, magnetic dipole components of magnetar strength are not consistent with optical data.

Subject headings: accretion, accretion disks — pulsars: general — stars: neutron — X-rays: bursts

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) constitute a special class of neutron star systems (Mereghetti et al. 2002; Hurley 2000; Woods & Thompson 2004). They are identified mainly through their X-ray luminosities ($L_X \sim 10^{34}$–10^{36} ergs s^{-1}), which are orders of magnitude higher than their rotational powers, $\dot{E}_{\rm rot} = I\Omega\dot{\Omega}$. Their spin periods are clustered to a very narrow range (5–12 s). All five known SGRs and two of the eight known AXPs show repetitive, short ($\lesssim$1 s) super-Eddington bursts with luminosities up to 10^{42} ergs s^{-1}. Three giant flares with peak luminosities $L_p > 10^{44}$ ergs s^{-1} and durations of a few minutes were observed from three different SGRs (Mazets et al. 1979, 1999; Hurley et al. 1999; Palmer et al. 2005).

The short timescales and the super-Eddington luminosities of these soft gamma-ray bursts strongly indicate a magnetar mechanism. The magnetar models (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996) have strong magnetic fields with magnitudes $B_* > 10^{14}$ G on the stellar surface to explain the burst energetics. Are the burst energies stored in the dipole component or in the higher multipoles of the magnetic field of the neutron star? In the current magnetar models, the dipole component of the magnetic field must be of magnetar strength to account for the spin-down properties of the AXPs and SGRs. In these models, persistent X-ray luminosities are explained by the magnetic field decay, while the magnetic dipole torque is taken to be the mechanism responsible for the spin-down rates of the sources.

In the alternative fallback disk model (Chatterjee et al. 2000; Alpar 2001), the source of the X-rays is the accretion onto the neutron star, while the optical/IR light originates from the accretion disk. The rotational evolution of the neutron star is determined by the interaction between the disk and the magnetosphere of the neutron star ($B_* \sim 10^{12}$–10^{13} G). Fallback disk models can account for the period clustering of AXPs and SGRs as the natural outcome of disk-magnetosphere interaction during their lifetimes (Alpar 2001; Ekşi & Alpar 2003). These models are consistent with magnetar fields on the neutron star provided that these fields are in higher multipole components of the magnetic field. As higher multipole fields rapidly decrease with increasing radial distance (as r^{-5} for the quadrupole component), it is the dipole component of the magnetic field that determines the interaction and the angular momentum transfer between the disk and the neutron star. In order to explain the period clustering of the AXPs and SGRs over their $\dot{M}$ history, the strength of the magnetic dipole field must be $B_* \sim 10^{12}$–10^{13} G (Alpar 2001; Ekşi & Alpar 2003).

Fallback disk models can also explain the enhancements observed in the persistent luminosities of SGRs and AXPs. The X-ray enhancement of SGR 1900+14 following its giant flare can be explained by the relaxation of a disk that has been pushed back by a preceding burst (Ertan & Alpar 2003). The same model with similar disk parameters can also reproduce the correlated X-ray and IR enhancement of AXP 2259+58, which lasted for ∼1.5 yr, if this is triggered by a burst, with a burst energy estimated to have remained under the detection limits (Ertan et al. 2006b).

The suggestion of fallback disks has motivated observational searches for disk emission in the optical and IR bands, and has resulted in various constraints on the models. Some of the AXPs were observed in more than one IR band (Hulleman et al. 2001; Israel et al. 2002; Wang & Chakrabarty 2002; Kaspi et al. 2003; Israel et al. 2003; Hulleman et al. 2004; Israel et al. 2004; Tam et al. 2004; Morii et al. 2005; Durant & van Kerkwijk 2006a). AXP 4U 0142+61 is the source with the most extended observations, as it was also observed in the optical *R* and *V* bands (Hulleman et al. 2000, 2004; Dhillon et al. 2005), and recently in mid-IR bands with the *Spitzer Space Telescope* (Wang et al. 2006). The discovery of modulation in the *R*-band luminosity of 4U 0142+61 at the neutron star's rotation period $P =$ 8.7 s, with a pulsed fraction of 27% (Kern & Martin 2002; Dhillon et al. 2005), is particularly significant. This fraction is much higher than the pulsed fraction of the X-ray luminosity of this source, indicating that the origin of the pulsed optical emission is not likely to be the reprocessed X-rays by the disk. Magnetospheric models for these pulsations can be built either with a dipole magnetar field or within a disk-star dynamo model (Cheng & Ruderman 1991), in which magnetospheric pulsar activity is sustained by a stellar dipole field of $\sim 10^{12}$ G and a disk protruding within the magnetosphere. Ertan & Cheng (2004) showed that this pulsed optical component of the AXP 4U 0142+61 can be explained by both types of magnetospheric models. Thus, the presence of strong optical pulsations from the magnetosphere does not rule out the possibility of a fallback disk with a 10^{12}–10^{13} G surface dipole magnetic field.

In the present work, we concentrate on the unpulsed optical/IR emission from the AXPs and SGRs in their persistent states, and we test the expectations of the irradiated accretion disk model through observations in different optical/IR energy bands (*V*, *R*, *I*, *J*, *H*, *K*, and K_s). The optical/IR emission expected from the

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TABLE 1
The Irradiated Disk Model and the Observational Flux Values

Band	J1708−40 Data ($A_V = 7.8$)	J1708−40 Model	1E 2259+58 Data ($A_V = 6.1$)	1E 2259+58 Model	4U 0142+61 Data ($A_V = 3.5$)	4U 0142+61 Model	1E 1841−045 Data ($A_V = 8.4$)	1E 1841−045 Model	1E 1048−59 Data ($A_V = 5.6$)	1E 1048−59 Model
	Flux (10^{-15} ergs s^{-1} cm^{-2})									
K_s	49	44	3.7	3.6	14	14	68	68	29	22
K	...	54	...	4.5	18	18	...	84	...	27
H	51	57	...	4.8	19	19	...	89	22	28
J	50	53	...	4.4	14	18	...	83	33	26
I	...	56	<15	4.4	18	21	...	88	...	24
R	...	65	<42	4.5	19	25	$<3.8 \times 10^5$	100	...	26
V	...	48	...	3.0	28	20	...	76	...	18

Note—The data flux values were calculated by using the magnitudes and A_V values given in the following references. For the 4U 0142+61, a plausible range for reddening is $2.6 < A_V < 5.1$ (Hulleman et al. 2004); the data for this source here correspond to $A_V = 3.5$. J1708−40: Durant & van Kerkwijk (2006a); Rea et al. (2003). 1E 2259+586: Hulleman et al. (2001); Woods et al. (2004). 4U 0142+61: Hulleman et al. (2000, 2004); Patel et al. (2003); Morii et al. (2005). 1E 1841−45: Wachter et al. (2004); Morii et al. (2003). 1E 1048−59: Wang & Chakrabarty (2002); Mereghetti et al. (2004).

irradiated fallback disks was first computed and discussed by Perna et al. (2000) and Hulleman et al. (2000). Using similar irradiation strengths, Perna et al. (2000) and Hulleman et al. (2000) found similar optical fluxes that remain well beyond those indicated by the observations of AXPs 4U 0142+61 and 1E 2259+586. To explain this result, Perna et al. (2000) suggested that the inner disk regions could be cut by an advection-dominated flow, while Hulleman et al. (2000) concluded that the then existing optical data of the AXP 4U 0142+61 (in the *I*, *R*, and *V* bands) can only be accounted for by an extremely small outer disk radius, around a few $\times\ 10^9$ cm. In the present work, we show that the optical/IR data of the AXPs can be explained by the irradiated accretion disk model without any implausible constraints on the outer and inner disk radii. The main reason for the difference between our results and those of earlier works is that both Hulleman et al. (2000) and Perna et al. (2000) assumed a particular irradiation strength, while we keep it as a free parameter, to address the broadband full data set. This approach is supported by the observations of the low-mass X-ray binaries (LMXBs) that indicate varying irradiation strengths. Furthermore, model fits are sensitive to the interstellar reddening parameter A_V, which was estimated to be between 2.6 and 5.1 for 4U 0142+61 (Hulleman et al. 2004). For this source, we obtain the best model fit with $A_V = 3.5$, which turned out to be consistent with the recent result of $A_V = 3.5 \pm 0.4$ (Durant & van Kerkwijk 2006b). On the other hand, the test disk model with an unreasonably small outer disk radius requires $A_V = 5.4$ (Hulleman et al. 2000). In this model, the optical emission comes from the outer disk, while in our model, it is the inner regions of an extended disk that emits substantially through the optical bands (see § 3 for further discussion). We give the details of the disk model in § 2. We discuss our results in § 3, and we summarize our conclusions in § 4.

2. OPTICAL/IR EMISSION FROM THE IRRADIATED DISK

Model fits to the X-ray and IR enhancement data (Kaspi et al. 2003) of AXP 1E 2259+586 favor the irradiated disk model, although they do not exclude the nonirradiated thin disk model (Ertan et al. 2006b). We start by assuming that the AXP disks are irradiated and include the irradiation strength as a free parameter through our calculations.

When the disk is irradiated by the X-rays from the neutron star, both the intrinsic dissipation and the irradiation flux should be taken into account in calculations of the disk blackbody emission. A steady disk model is a good approximation for the present evolution of the AXP and SGR disks in their persistent states. For a steady thin disk, the intrinsic dissipation can be written as $D = (3/8\pi)(GM\dot{M}/R^3)$, where $\dot{M}$ is the disk mass flow rate, M is the mass of the neutron star, and R is the radial distance from the neutron star (see, e.g., Frank et al. 2002). In the absence of irradiation, the effective temperature $T_{\rm eff}$ of the disk is proportional to $R^{-3/4}$ for a given $\dot{M}$. For an irradiated disk, the irradiation flux can be written as $F_{\rm irr} = \sigma T_{\rm irr}^4 = (C\dot{M}c^2)/(4\pi R^2)$, where c is the speed of light (Shakura & Sunyaev 1973). Irradiation parameter C includes the albedo of the disk face, the disk geometry, and the conversion efficiency of the accretion into X-rays. Irradiation temperature $T_{\rm irr} = (F_{\rm irr}/\sigma)^{1/4}$ is proportional to $R^{-1/2}$. For small radii, dissipation is the dominant source of the disk emission. At a critical radius R_c, the irradiation flux becomes equal to the dissipation rate, and beyond R_c, the disk emission is supported mainly by reprocessed X-rays. Equating $F_{\rm irr}$ to D, the critical radius is found to be $R_c = (3GM_*)/(2Cc^2) \simeq (10^{-4}/C)3 \times 10^9$ cm. The effective temperature profile of the disk can be obtained using $\sigma T^4 = D + F_{\rm irr}$, where σ is the Stefan-Boltzmann constant.

We adopt the observed magnitudes in the optical/IR bands, distances, and the $N_{\rm H}$ values given by Woods & Thompson (2004 and references therein) and convert the magnitudes to energy flux values. We calculate A_V values using $N_{\rm H} = 1.79 \times 10^{21} A_V$ (Predehl & Schmitt 1995). To find the model disk flux in a given observational band, we integrate the calculated blackbody emissions of all radial grids radiating in this band. For comparison with data, we calculate the model disk fluxes along the optical/IR bands *V*, *R*, *H*, *I*, *J*, *K*, and K_s. For all sources, we set $\cos i = 1$, where i is the angle between the disk normal and the line of sight of the observer. We equate the disk mass flow rate $\dot{M}$ to the accretion rate onto the neutron star, thus assuming that the mass loss due to the propeller effect is negligible. We first adjust $\dot{M}$ to obtain the observed X-ray flux. Next, using this value of $\dot{M}$ and taking the strength of the magnetic dipole field $B_* = 10^{12}$ G on the surface of the neutron star, we calculate the Alfvén radius $R_{\rm A}$, which we take to be the inner radius of the disk. Then we look for a good fit to the overall available optical/IR data by adjusting the irradiation strength C within the uncertainties discussed in § 3.

3. RESULTS AND DISCUSSION

Our results are summarized in Table 1. For each source, the first column gives the unabsorbed flux data obtained from the observed magnitudes and the estimated A_V values (see Table 1) given in Woods & Thompson (2004), and the second column

TABLE 2
The Parameters of the Irradiated Disk Model

Parameter	1RXS J1708−40	1E 2259+58	4U 0142+61	1E 1841−045	1E 1048−59
R_{in} (cm)	1.2×10^9	2.3×10^9	1.0×10^9	1.3×10^9	3.3×10^9
C	5.0×10^{-4}	1.6×10^{-4}	1.0×10^{-4}	7.2×10^{-4}	7.0×10^{-4}
d (kpc)	5	3	3	7	3
$\dot{M}$ (g s^{-1})	1.0×10^{15}	9.1×10^{13}	4.8×10^{14}	2.2×10^{15}	1.3×10^{14}

Note.—This model gives the optical/IR flux values seen in Table 1. For all the sources, we set $\cos i = 1$, where i is the inclination angle between the disk normal and the line of sight of the observer, and we take the outer disk radius to be $R_{out} = 5 \times 10^{12}$ cm (see § 3 for details).

gives the model fluxes. For the AXP 4U 0142+61, the range of reddening quoted in earlier literature is $2.6 < A_V < 5.1$ (Hulleman et al. 2004). We obtain a good fit with $A_V = 3.5$. Table 1 shows that the irradiated steady disk model is in agreement with all the AXPs observed in the optical and IR bands. The parameters of the model for each source are given in Table 2.

At present, AXP 4U 0142+61, which has been observed in five different optical/IR bands from K to V in the same X-ray luminosity regime, seems to be the best source for studying the properties of AXPs in the persistent state. Earlier work by Hulleman et al. (2000) excluded the disk model for the AXP 4U 0142+61. They obtained an irradiation temperature profile by using a particular irradiation strength. The estimated optical flux for an extended disk with this irradiation efficiency remains above the optical data points of the AXP 4U 0142+61 (see Fig. 3 in Hulleman et al. 2000). Considering the possibility that the optical flux might originate from the outermost disk region, Hulleman et al. (2000) tried to fit the then observed three data points in the I, R, and V bands to the Rayleigh-Jeans tail of a blackbody spectrum with the extinction parameter $A_V = 5.4$. This placed an upper limit on the outer disk radius that is too small for a realistic disk. The key factor in the difference between the earlier results and our recent results is the irradiation efficiency, which we allow to vary in conjunction with A_V, to provide the best fit to the current broadband data. We note that the irradiation efficiency indicated by the observations of the low-mass X-ray binaries varies from source to source. Even for the same source, the ratio of the irradiation flux to the X-ray flux may change with accretion rate (de Jong et al. 1996; Dubus et al. 1999; Ertan & Alpar 2002). Taking these things into account, we keep the irradiation efficiency as a free parameter for our model fits. With the parameters given in Table 2, the irradiated disk model can account for the optical/IR data of this source without setting any stringent constraints on the inner or outer disk radii. In our model, the optical luminosity is radiated from the inner disk, while longer wavelength IR emission comes from larger radii. A more detailed analysis of the AXP 4U 0142+61 with the new detections in the mid-IR *Spitzer* bands confirms the results here (Ertan et al. 2006a). The irradiation parameter C obtained from our model fits turned out to be in the range ($10^{-4} < C < 10^{-3}$) estimated from the observations of LMXBs and the disk-stability analyses of the soft X-ray transients (de Jong et al. 1996; Dubus et al. 1999; Ertan & Alpar 2002). Within the critical radius R_c, dissipation is the dominant heating mechanism. For the disk model of the AXP 4U 0142+61, $R_c \simeq 3 \times 10^9$ cm, and $R_{in} = 1 \times 10^9$ cm. The innermost disk emitting mostly in the UV bands also contributes to the optical emission. The radial distance at which the disk blackbody temperatures peak at the optical bands (R, V) is about 10^{10} cm; at this radial distance, about 35% of of the optical radiation is due to dissipation, and the rets is due to irradiation. Peak temperatures of the IR bands from I to K_s lie between $R \sim 2 \times 10^{10}$ cm and $R \sim 1.5 \times 10^{11}$ cm.

There are several uncertainties related to the inner disk emission characteristics of the AXPs, which are not possible to address by the irradiated thin disk model. First, emission properties of the innermost disk boundary interacting with the magnetosphere are not very clear. Second, the contributions from the magnetospheric pulsed emission, which is known to have a fraction of about 27% in the R band for 4U 0142+61, is likely to be radiated from the other IR and optical bands as well. The relative amplitudes of these pulsed contributions radiated from different optical/IR bands are not known at present. Finally, there could be some X-ray–shielding effects depending on the details of the geometry of the innermost disk regions, which could also affect the optical/IR emission properties of these sources. For all the AXPs that were detected in the optical/IR bands, the optical and IR flux values of our models remain within about 30% of all the data points, which is a reasonable fit considering the uncertainties discussed above.

For AXP J1708−40, Durant & van Kerkwijk (2006a) recently found that the previously reported IR data in the K_s, H, and J bands are likely to be of a background star. They found another object within the positional error cycle and argued that this second object is more likely to be the IR counterpart to the AXP J1708−40. For this source, we adopt the IR (K_s, H, J) data set reported by Durant & van Kerkwijk (2006a).

For the persistent state of the AXP 1E 2259+586, we use the preenhancement data (Hulleman et al. 2001). This source was detected in the K_s band, and there are upper limits for the I and R bands. Our model flux values are 3 and 10 times below the upper limits reported for the I and R bands, respectively.

AXP 1E 1048−59 was detected in the K_s, H, and I bands (Wang & Chakrabarty 2002). Observed X-ray fluxes from this source between 2000 December and 2003 January show a variation within a factor of 5 (Mereghetti et al. 2004). We use the X-ray flux obtained from the nearest X-ray observation to the date of the IR observations.

AXP 1E 1841 was detected only in the K_s band, and there is a high upper limit in the R band (Wachter et al. 2004). Model estimates in other optical/IR bands for this source (and the other AXPs) can be tested by future optical and IR observations.

Since there are no detections in short-wavelength optical bands for the AXPs (except for 4U 0142+61), model fits are not sensitive to the chosen inner disk radii. We equate the inner disk radii to the Alfvén radii (Table 2) corresponding to a magnetic field with magnitude $B_* = 10^{12}$ G on the stellar surface and the accretion rates derived from the estimated X-ray luminosities (see Table 1 for references). For the AXP 4U 0142+61, optical data in the R and V bands provide a constraint for the inner disk radius, thereby providing a constraint for the strength of the magnetic dipole field of this source (see § 4).

4. CONCLUSION

We have shown that the optical, infrared, and X-ray observations of the AXPs in their persistent states can be explained with irradiated disk models. Among the AXPs, 4U 0142+61 is currently the only source that provides an upper limit for the inner disk radius through its optical (*R*, *V*) data. For the best model fit for this source, which we have obtained with $A_V = 3.5$, the model inner disk radius ($\sim 10^9$ cm) is around the Alfvén radius for the accretion rate, estimated from the X-ray luminosity, together with a dipole magnetic field strength $B_* \simeq 10^{12}$ G on the neutron star surface. Nevertheless, it is possible to obtain reasonable fits by increasing the inner disk radius and decreasing the reddening accordingly. For $A_V = 2.6$, the minimum value of the reddening in the range $2.6 < A_V < 5.1$ (Hulleman et al. 2004), we obtain the best fit with $R_{\rm in} \simeq 8 \times 10^9$ cm that corresponds to the maximum reasonable dipole field strength $B_* \simeq 4 \times 10^{13}$ G on the pole and half of this value on the equator of the neutron star. We note that these limits could be increased depending on the amount of possible mass loss due to the propeller effect and/or on how much the inner disk radius penetrates inside the Alfvén radius (see Ertan et al. 2006a for a detailed discussion of 4U 0142+61). On the other hand, even including these possibilities, very recent analysis concluding that $A_V = 3.5 \pm 0.4$ (Durant & van Kerkwijk 2006b) implies surface dipole magnetic field strengths less than about 10^{13} G. While the magnetar fields ($B_* > 10^{14}$ G) in multipoles are compatible with this picture, optical (*R*, *V*) data excludes a hybrid model involving a disk surrounding a magnetar dipole field. In the latter case, inner disk regions emitting in the optical would be truncated by the magnetar dipole field. High magnetic fields in multipoles, on the other hand, decrease rapidly with increasing radial distance, and they do not affect the disk-magnetosphere interaction.

On the other hand, existing IR data of the AXPs, including recent observations of 4U 0142+61 by *Spitzer* in 4.5 and 8 μm bands (Wang et al. 2006), do not put an upper limit on the extension of the outer disk radius $R_{\rm out}$. The lower limit for $R_{\rm out}$ provided by the longest wavelength IR data of the AXP 4U 0142+61 is around 10^{12} cm. Further observations in the longer wavelength infrared bands by the *Spitzer Space Telescope* will provide us with valuable information about the structure and possibly the extension of the fallback disks around these systems. As a final remark, some AXPs and SGRs that are under the detection limits in some of the optical and IR bands could be observed in these bands if they exhibit phases of enhanced emission, as observed in the SGR 1900+14 and the AXP 1E 2259+586.

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