Can the anomalous X-ray pulsars be powered by accretion?

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ABSTRACT

The nature of the 5 − 12 s “anomalous” X-ray pulsars (AXPs) remains a mystery. Among the models that have been proposed to explain the properties of AXPs, the most likely ones are: (1) isolated accreting neutron stars evolved from the Thorne-Żytkow objects (TŻOs) due to complete spiral-in during the common envelope (CE) evolution of high-mass X-ray binaries (HMXBs), and (2) magnetars, which are neutron stars with ultra-high (≈ 10^{14} − 10^{15} G) surface magnetic fields. We have critically examined the predicted change of neutron star’s spin in the accretion model, and found that it is unable to account for the steady spin-down observed in AXPs. A simple analysis also shows that any accretion disk around an isolated neutron star has extremely limited lifetime. A more promising explanation for such objects is the magnetar model.

Subject headings: accretion, accretion disks - binaries: close - pulsars: general - stars: neutron - X-ray: stars

1. Introduction

In recent years there has been growing evidence that there is a class of pulsating objects, referred to as braking X-ray pulsars (Mereghetti & Stella 1995) or anomalous X-ray pulsars (AXPs, van Paradijs, Taam, & van den Heuvel 1995), characterized by the following common features (see Stella, Israel, & Mereghetti 1998 for a recent review): (1) similar spin periods in ∼ 5 − 12 s range; (2) steady spin-down on a timescale of ∼ 10^4 − 10^5 yr; (3) relatively low and constant X-ray luminosities of ∼ 10^{35} − 10^{36} erg s^{-1}; (4) very soft X-ray spectra, typically described by a combination of a blackbody of effective temperature ∼ 0.3 − 0.4 keV and a power law with a photon index ∼ 3 − 4; (5) no detected optical counterpart, some possibly associated with supernova remnants. These sources originally include 1E 2259+586, 1E 1048.1−5937, 4U 0142+61 and RX J1838.4−0301 (see Mereghetti, Belloni, & Nasuti 1997 for an alternative interpretation of this system). The recently discovered X-ray pulsars 1E 1841−045 (Vasisht & Gotthelf 1997), RX J0720.4−3125 (Haberl et al. 1997), 1RXS J170849.0−400910 (Sugizaki et al. 1997) and PSR J1844−0258 (Gotthelf & Vasisht 1998; Torii et al. 1998) may also belong to the group of AXPs.

Models proposed to explain the properties of AXPs fall into two main categories: (1) Neutron stars accreting from a binary companion with very low mass (Mereghetti & Stella 1995), or isolated neutron stars accreting from circumstellar debris (e.g., Corbet et al. 1995). In the latter case, in particular, van Paradijs et al. (1995) proposed that these pulsars are young (∼ 10^5 yr) descendants of the TŻOs (Thorne & Żytkow 1977): neutron stars surrounded by the remnants of the CE evolution of HMXBs. Based on this picture, Ghosh et al. (1997) argued that the accretion flow onto AXPs from the collapsed envelope may consist of two components: a spherical component with low-angular momentum, giving rise to the
black body emission from a considerable fraction of the neutron star surface, and a disk component with high-angular momentum responsible for the power-law emission and for the long-term spin-down. (2) Magnetars (Thompson & Duncan 1996; Vasisht & Gotthelf 1997) - neutron stars with a very strong ($\sim 10^{14} - 10^{15}$ G) magnetic field, in which the magnetic field, rather than rotation, provides the main source of free energy, and the decaying field powers the X-ray emission. The observed X-ray luminosities and X-ray spectra in AXPs also follow naturally from this model (Thompson & Duncan 1996).

Since both kinds of models seem to present a reasonable description of the evolution and the energy source of AXPs, in this paper we examine the dynamical properties of the accretion models, in view of the observed secular spin change in AXPs. We focus on the isolated, accreting neutron star model, since optical, dynamical and evolutionary limits seem to argue against binarity in AXPs (e.g., van Paradijs et al. 1995). Our conclusion is that accretion models may not be favored for AXPs.

2. The accretion models for AXPs

The accretion flow around an AXP could be quasi-spherical or in the form of a disk, depending on the specific angular momentum carried by the accreting material in the collapsed common envelope. As argued by Ghosh et al. (1997), disk accretion flow in AXPs reaches the stellar surface in field-aligned flow onto the two polar caps of the neutron star that occupy a very small fraction of the total surface area, while plasma from quasi-spherical accretion flow is not completely disrupted in the stellar magnetosphere, and does not become fully field-aligned before it reaches the stellar surface, so that the entire stellar surface is available for accretion. To explain the blackbody component (which contributes up to 50% of the total X-ray luminosity, see Stella et al. 1998) with an effective radius of order the stellar radius, an exterior quasi-spherical accretion flow is generally required. Below we discuss two kinds of accretion models for AXPs: the spherical accretion model and the two-component (disk + spherical) accretion model.

2.1. The spherical accretion model

Because of symmetry of accretion and small angular momentum, a spherical accretion flow generally exerts a nearly zero net torque on the accreting star. A possible spin-down mechanism for spherically accreting neutron stars was suggested by Illarionov & Kompaneets (1990) – when the X-ray luminosity of a neutron star lies between $\sim 10^{34}$ and $\sim 10^{36}$ erg s$^{-1}$, roughly in accordance with those of AXPs, an outflowing stream of magnetized matter can be formed within a limited solid angle, the neutron star loses angular momentum when the outflow forms so deep as to capture the magnetic field lines from the rotating magnetosphere.

The outflow formation is, however, connected with the anisotropy and the intensity of the hard X-ray emission of the neutron star. It requires that X-rays from the pulsar heat the accreting matter anisotropically through Compton scattering, so that the heated matter has a lower density than the surrounding accreting matter, and flows up by the action of the buoyancy force (Illarionov & Kompaneets 1990; Igumenshchev, Illarionov, & Kompaneets 1993). This mechanism is most effective for the hard X-ray transients (Be/X-ray binaries) due to their especially hard X-ray spectra and high X-ray variability, but fails in AXPs because of their soft X-ray spectra and almost constant X-ray luminosities.

Another possible spin-down mechanism for AXPs is the conventional “propeller” mechanism (Illarionov
& Sunyaev 1975) - when the magnetospheric radius \( R_m \) becomes larger than the corotation radius \( R_c \equiv [G M P^2/(4\pi^2)]^{1/3} \) (where \( G \) is the gravitation constant, \( M \) mass of the neutron star, and \( P \) the spin period), mass accretion becomes inhibited by the centrifugal barrier, the star expels the material once it spins up the material to the local escape velocity at \( \sim R_m \). Actually, a strong support for the idea that X-ray emission in AXPs is powered by accretion comes from the argument that AXPs are spinning near the equilibrium period \( P_{\text{eq}} \sim 5 - 12 \text{ s} \), corresponding to their observed X-ray luminosities of \( \sim 10^{35} - 10^{36} \text{ erg s}^{-1} \) and inferred magnetic field strengths of \( \sim 10^{11} \text{ G} \) (Mereghetti & Stella 1995; van Paradijs et al. 1995). Note that even in the propeller regime, a significant amount of the quasi-spherically accreting material might still leak through “between the field lines” and reach the neutron star surface (Arons & Lea 1980). Evidence for propeller effects has been found in the X-ray pulsars GX 1+4 and GRO J1744-28 (Cui 1997), and in the soft X-ray transient source Aql X-1 (Zhang et al. 1998). In these sources the occurrence of the propeller effect is due to variable mass transfer rate from the companion star. For AXPs, it is difficult to imagine why the (almost constant) accretion rates are so finely-tuned to put them at the edge of the propeller regime, i.e., \( R_m \sim R_c \): if \( R_m < R_c \), AXPs should behave similarly as other normal wind-fed X-ray pulsars (with random walk like spin change); if \( R_m > R_c \), AXPs would be characterized by weak X-ray pulsations, contradicted with observations.

### 2.2. The two-component accretion model

Spin-down in disk-fed pulsars is naturally expected in the standard magnetized accretion disk model (Ghosh & Lamb 1979a, 1979b), in which the (dipolar) stellar magnetic field is assumed to penetrate the disk and wound up in the toroidal direction, because of the angular velocity difference between the accretion disk and the star. The magnetic field lines penetrating the disk between the inner radius \( R_0 \) of the disk and the corotation radius \( R_c \) spin up the star, while those penetrating the accretion disk outside the corotation radius brake the star. The spin evolution of the star is therefore the result of a balance between the angular momentum carried by the accreting matter from the disk to the star, the magnetic spin-up torque from the accretion disk inside the corotation radius, and the magnetic spin-down torque from the accretion disk outside the corotation radius, i.e.,

\[
\dot{I} = \dot{M} (G M R_0)^{1/2} n(\omega_s),
\]

where \( I \) and \( \Omega_s \) are the moment of inertia and the angular frequency of the neutron star, respectively. The dimensionless torque \( n(\omega_s) \) depends on the “fastness parameter” \( \omega_s \), the ratio between \( \Omega_s \) and the Keplerian angular frequency of disk plasma at \( R_0 \), \( \omega_s \equiv \Omega_s / \Omega_k(R_0) = (R_0/R_c)^{3/2} \): when \( 0 < \omega_s < \omega_c \), \( n > 0 \), the star spins up; when \( \omega_c < \omega_s < 1 \), \( n < 0 \), the star spins down. Here \( \omega_c \) is the critical value of \( \omega_s \) where the torque vanishes (\( n=0 \)), which may lie in the range \( 0.71 - 0.95 \) (Wang 1995; Yi 1995; Li & Wang 1996). This means that the parameter space for spin-down in a disk-accreting neutron star (\( 0.71 - 0.95 < \omega_s < 1 \)) is rather small compared to spin-up.

The standard accretion disk model, however, cannot be adequately applied to AXPs. First, for simplicity of investigation, Ghosh & Lamb assumed that the stellar spin axis aligns the dipole magnetic moment, while X-ray pulsars are obviously oblique rotators. We mention that Wang (1997) recently evaluated the torque exerted on an oblique rotating star by a magnetized accretion disk, and found that when the dipole inclination angle increases, the vertical magnetic flux through the disk decreases, and the spin-down contribution to the torque weakens, which is unable to offset the spin-up torque for inclinations exceeding some limiting value (\( \sim 54^\circ - 67^\circ \)), even when the fastness parameter approaches unity. This implies that disk-fed X-ray pulsars are more likely to be spinning up than spinning down.
Now consider the two-component (disk + spherical) accretion flow onto the neutron star. When the quasi-spherical flow begins to interact with the stellar magnetic field, a magnetosphere is formed around the neutron star, the spherical inflow passes through a shock at the magnetospheric boundary, cools, and enters the magnetosphere through Rayleigh-Taylor instability (Arons & Lea 1976, 1980). Since plasma around the magnetosphere is highly diamagnetic, the stellar magnetic field lines would be confined inside the magnetosphere, unable to stretch out and to penetrate the disk outside the magnetosphere to produce a magnetic torque on the star, as originally suggested for the pure accretion disk model by Ghosh & Lamb (1979a, 1979b). The fact that the blackbody component contributes a considerable fraction of the total X-ray luminosity in AXPs implies that the accretion rate in the spherical flow is roughly comparable to that in the disk flow, or $R_m \sim R_0$. Both the magnetospheric radius $R_m$ and the inner disk radius $R_0$ should be no larger than the corotation radius $R_c$ for accretion to occur, the star would always experience a spin-up torque from the most inner region of the disk inside $R_m$, that is, in the two-component accretion model, AXPs should be observed to be spinning up rather than spinning down.$^2$

2.3. How long can a disk be sustained?

If we relax our arguments and assume that some unknown mechanisms could balance the spin-up torque and bring the pulsars to equilibrium spin, then there exists an alternative explanation for the secular spin-down in AXPs, that is, it is caused by the long-term decrease in the mass accretion rate (Ghosh et al. 1997). Since there is no supply to the disk in the AXP phase, the disk accretion rate $\dot{M}$ should show a steady, secular decrease on the viscous timescale, $\tau_\dot{M} \sim \tau_{\text{visc}} \approx 2 \times 10^5 (\alpha/0.1)^{-1} (R_{\text{out}}/10^{14} \text{ cm})^{3/2} \text{ yr}$ as the disk dissipates. Here $\alpha$ is the conventional disk viscosity parameter (Shakura & Sunyaev 1973), and $R_{\text{out}}$ is the outer edge of the disk. Because the equilibrium period $P_{\text{eq}}$ scales with $\dot{M}$ roughly as $P_{\text{eq}} \propto \dot{M}^{-3/7}$, at equilibrium, a secular, monotonic spin-down is expected on a timescale

$$\frac{P}{\dot{P}} \approx \left(\frac{7}{3}\right) \tau_\dot{M} \sim 5 \times 10^5 (\alpha/0.1)^{-1} (R_{\text{out}}/10^{14} \text{ cm})^{3/2} \text{ yr},$$

(2)

roughly in accordance with the observations if $R_{\text{out}} \sim 10^{13} \text{ cm}$. [Note that in Ghosh et al. (1997, p720) the quantity relating $P/\dot{P}$ and $\tau_\dot{M}$ should be 7/3 rather 3/7.]

To comment on this scenario, we first point out that Ghosh et al. (1997) have used an inappropriate estimate of the viscous timescale in the disk. These authors assumed an outer radius of the disk as large as $\sim 10^{14} \text{ cm}$, comparable to the radius of the TZO envelope, but derived equation (2) by adopting the prescriptions for middle region (b) of the Shakura & Sunyaev (1973) disks, which is limited to $\sim (4 \times 10^7 - 2 \times 10^8) \text{ cm}$ for mass accretion rates relevant for AXPs ($\sim 10^{15} - 10^{16} \text{ g s}^{-1}$). As a result, $\tau_\dot{M}$ was not estimated self-consistently.

A prerequisite for spin-down driven by a decrease in $\dot{M}$ is that, for any change in the accretion rate, the accretion torque could respond promptly so that the star’s spin is always around the instantaneous

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$^2$The enigmatic transition between spin-up and spin-down in the 7.66 s low-mass X-ray binary 4U 1626-67 (Chakrabarty et al. 1997) seems to provide an exception to the above argument. It appears to be fed by Roche lobe overflow from a low-mass ($0.02 - 0.06 M_\odot$) degenerate He or CO dwarf companion (Verbunt, Wijers, & Burm 1990), and its spectrum has a large quasi-thermal component, plus an extended hard component, although it has been excluded from the AXP group by various authors. The existing magnetized disk models are unable to provide an explanation for such torque reversal. It was recently suggested that the sense of rotation of the disk in 4U 1626-67 has been changed (Nelson et al. 1997), possibly because of a warping instability in the disk due to irradiation from the central X-ray source (van Kerkwijk et al. 1998).
equilibrium, i.e., $\tau_M$ should be much longer than $\tau_\Omega$, the characteristic timescale on which the spin frequency $\Omega_s$ evolves towards the equilibrium frequency $\Omega_{eq}$, if the mass accretion rate is constant (Henrichs 1983). The latter can be estimated in the similar way as in Henrichs (1983): Assuming a simple form of the dimensionless torque,

$$n(\omega_s) = \frac{1 - \omega_s/\omega_c}{1 - \omega_a/\omega_c}$$

with an intermediate value of $\omega_c \simeq 0.7$, we may use a linear approximation of $n(\omega_s)$ around $\omega_s = \omega_c$,

$$n(\omega_s) \simeq -5\omega_s + 3.5.$$  

For a constant mass accretion rate, $\omega_s$ is proportional to $\Omega_s$, and we may write

$$\dot{\Omega}_s(t) = a\Omega_s(t) + b,$$

where $a \simeq -5\dot{M}R_0^2/I$ and $b \simeq 3.5\dot{M}(GMR_0)^{1/2}/I$. Solving for $\Omega_s(t)$ we obtain:

$$\Omega_s(t) = \Omega_{eq} - (\Omega_{eq} - \Omega_0)e^{-t/\tau_\Omega},$$

where $\Omega_0$ is the angular frequency at $t = 0$, and $\tau_\Omega = -1/a = \Omega_s/b$ or, numerically,

$$\tau_\Omega \simeq 8.7 \times 10^4 \mu_{29}^{-8/7} L_{35}^{-3/7} \text{ yr},$$

where $\mu_{29}$ is the magnetic moment in units of $10^{29}\text{G cm}^3$, and $L_{35}$ is the X-ray luminosity in units of $10^{35}\text{erg s}^{-1}$. [Throughout this paper, we adopt typical values of the mass ($1.4M_\odot$) and radius ($10^6\text{ cm}$) for a neutron star.] In Table 1 we have listed the observed values of $P$ and $L_{35}$ for four AXPs, 1E 2259+586, 4U 0142+61, 1E 1048.1−59 (Stella et al. 1998 and references therein) and 1E 1841−05 (Vasisht & Gotthelf 1997). Also listed are the derived values of $\mu_{29}$, $\tau_\Omega$ and $\tau_M$. We use the values of $\mu_{29}$, obtained by assuming that these pulsars are at equilibrium spin, to estimate $\tau_\Omega$ through equation (7). The evolutionary timescales of the mass accretion rate $\tau_M$, are derived from the observed spin-down timescales, $\tau_M = (3/7)(P/\dot{P})$ (For 1E 1841−05, the spin-down timescale is not known, and is assumed to be less than the age of the associated supernova remnant Kes 73, $\sim 2000\text{ years}$, see Vasisht & Gotthelf 1997). From Table 1 it is clearly seen that the assumption $\tau_M \gg \tau_\Omega$ collapses in at least some of the AXPs with shorter spin-down timescale, say, 1E 1048.1−59, and PSR J1841−045. (Adopting other forms for the dimensionless torque $n(\omega_s)$ only slightly changes the values of $\tau_\Omega$; see Henrichs 1983.)

To further examine the fate of the disks around AXPs, one needs a reasonable estimate of the disk size. This can be made in several ways. (1) In view of stellar evolution, the characteristic radius of the disk formed from the CE evolution is of order the initial binary separation, $\sim 3 \times 10^{11}\text{ cm}$ for an HMXB initially consisting of a $1.4M_\odot$ neutron star and a $15M_\odot$ companion with an orbital period of 10 days (Podsiadlowski et al. 1995). If the accretion disk is acquired when the newly formed neutron star is kicked toward a stellar companion, the characteristic radius of the disk at formation is $\sim GM/V^2_{\text{disk}} \simeq (2 \times 10^{10}\text{cm})(V_{\text{kick}}/10^3\text{ km s}^{-1})^{-2}$, provided that the density gradient scale inside the stellar companion is comparable (Thompson & Duncan 1996). (2) Limits on the optical and infrared emission from an extended disk may severely constrain disk-fed AXP models (Thompson & Duncan 1996). Recent deep infrared and optical observations by Coe & Pighton (1998) show that, in the case of 1E 2259+586, the limits of $J \geq 20$ and $K \geq 18.5$ imply a limiting disk size of $\sim 7 \times 10^{10}\text{ cm}$ for a 2500 K blackbody at 4.5 kpc; the infrared limits for 4U 0142+62 are similar and imply a disk size of $7 \times 10^9 - 3 \times 10^{10}\text{ cm}$ for a distance of $0.5 - 2.0\text{ kpc}$. (3) The current size of the disk can also be restricted by the stability analysis. The persistent nature of AXPs indicates that the accretion disks (if they exist) are stable against the
thermal-viscous instability (Frank, King, & Raine 1992), requiring that the temperature at the outer edge of the disk should be higher than the hydrogen ionization temperature \( \sim 6500 \text{ K} \). Recent calculations by Dubus et al. (1999) reveal that the critical accretion rate in the irradiated disk, below which no steady disk solution can exist, is given by

\[
\dot{M}_{\text{cr}} \simeq 1.3 \times 10^{15} \left( \frac{R_{\text{out}}}{10^{10} \text{ cm}} \right)^{2.1} \left( \frac{C}{5 \times 10^{-4}} \right)^{-0.5} \text{ g s}^{-1},
\]

where the quantity \( C \) includes the efficiency of X-ray production from accretion, the X-ray albedo of the disk, and the disk opening angle, with the typical value of \( 5 \times 10^{-4} \). If the X-ray emission from AXPs is due to accretion, equation (8) implies that currently the outer radius of the disk in AXPs is \( R_{\text{out}} \sim 10^{10} \text{ cm} \), comparable with the estimates in point (2). If the disk had a larger size, plasma in the disk outside of \( \sim 10^{10} \text{ cm} \) would always be in the cold, neutral state (since there is no mass supply, as in binary systems, to increase the surface density in the disk), with an accretion rate much smaller than in the hot, ionized, inner disk, and finally would be separated away from the disk.

For region (c) in the Shakura & Sunyaev (1973) disks, the viscous timescale is (e.g., Frank, Raine, & King 1992)

\[
\tau_{\text{visc}} \sim 0.1 \left( \frac{\alpha}{0.1} \right)^{-0.8} \left( \frac{\dot{M}}{10^{15} \text{ g s}^{-1}} \right)^{-0.3} \left( \frac{R_{\text{out}}}{10^{10} \text{ cm}} \right)^{1.2} \text{ yr},
\]

which is much shorter than the observed spin-down timescale or the estimated age of AXPs, unless the viscous parameter \( \alpha \) is extremely small. This suggests that the disk would dissipate soon after its formation, and that evolution of mass accretion rate in the disk is too rapid to account for the observed spin-down timescale.

We conclude that an accretion disk in AXPs can live with very short lifetime, and is unable to spin down the pulsars as observed.

3. Discussion and conclusion

By examining the possible spin-down processes in the hypothesized accretion flow around AXPs, we are led to the conclusion that accretion may not be favored as the energy source in AXPs, no matter whether it has a spherical or disk geometry. In this sense the magnetar model seems to be more promising, since the narrow range of the spin periods and the spin-down timescale can be naturally accounted for under the assumption that the neutron star is isolated and has spun down by the torque of a relativistic MHD wind, approximated as magnetic dipole radiation (Thompson & Duncan 1996). This is strengthened by the recent measurements of ultra-high magnetic field strengths of \( \sim 10^{14} – 10^{15} \text{ G} \) in two soft-gamma ray repeaters SGRs 1806-20 (Kouveliotou et al. 1998a) and 1900+14 (Kouveliotou et al. 1998b), which possess similar spin periods (7.47 s and 5.16 s respectively) to the AXPs. However, we note that, it still remains open whether all of the sources mentioned in §1 form a homogeneous group, and can be described by a unified model (for example, there are considerable diversities in the spectrum of individual source). In the case of 1E 2259+586, fluctuations in the spin-down rate seem to be consistent with the torque noise measured in accreting X-ray pulsars, supporting the accretion model (Baykal & Swank 1996), though they could also be

\(^3\)Note that the estimate of \( \tau_{\text{visc}} \) for a stable disk is almost independent on irradiation, since the inner structure of the disk is not essentially altered by the central X-ray source (e.g., Dubus et al. 1999 and references therein), especially in the case of AXPs, in which most of the energy in X-rays, because of their soft nature, is absorbed at only the surface of the disk.
explained by neutron star glitch and magnetic field evolution (Thompson & Duncan 1996). Especially, the spin trend of the newly discovered pulsars (RX J0720.4-3125, 1RXS J170849.0-400910 and PSR J1844-0258) is unknown. Further X-ray observations, for example, by measuring the long-term stability of the X-ray fluxes, secular trends in the pulse periods, are required to secure the classification of these pulsars to the growing family of AXPs, and to confirm or reject the proposed theoretical models.

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Kouveliotou, C. et al. 1998a, Nat, 393, 235

Table 1: Observed and derived parameters of four AXPs

<table>
<thead>
<tr>
<th>Source</th>
<th>$P$ (s)</th>
<th>$L_{35}$</th>
<th>$\mu_{29}$</th>
<th>$\tau_{\Omega}$ (yr)</th>
<th>$\tau_{\dot{M}}$ (yr)</th>
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<tr>
<td>1E 2259+586</td>
<td>6.98</td>
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<td>4U 0142+61</td>
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<td>3.3</td>
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<td>1E 1048.1−59</td>
<td>6.44</td>
<td>0.2</td>
<td>0.7</td>
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<tr>
<td>1E 1841−05</td>
<td>11.76</td>
<td>3.5</td>
<td>5.5</td>
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<td>$\lesssim 1.0 \times 10^3$</td>
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