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Citation

Menou, Kristen, Rosalba Perna, and Lars Hernquist. 2002. "Hydrogen-Poor Disks in Compact X-Ray Binaries." *The Astrophysical Journal* 564 (2): L81–84. <https://doi.org/10.1086/338909>.

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Hydrogen-Poor Disks in Compact X-Ray Binaries

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ABSTRACT

We show that accretion disks in several compact X-ray binaries with hydrogen-depleted donors are likely subject to a thermal ionization instability, unless they are strongly irradiated. These disks are particularly interesting in that their MHD-turbulent properties in the neutral phase may be quite different from those of standard, hydrogen-rich disks.

subject headings: X-ray: stars – accretion, accretion disks – MHD – turbulence

1. Introduction

The vast majority of accretion disks around compact objects in close binary star systems are composed of hydrogen-rich material, as a result of Roche-lobe mass-transfer or wind-capture from a non-degenerate companion star (see Lewin, van Paradijs & van den Heuvel 1995 and Warner 1995 for reviews). It has long been known that such hydrogen-rich disks are subject to a thermal-viscous instability occurring when hydrogen becomes partially ionized, at central (mid-plane) temperatures $T_c \sim 10^4$ K (or, equivalently, disk effective temperatures $T_{\text{eff}} \lesssim 10^4$ K; Meyer & Meyer-Hofmeister 1981; see, e.g., Cannizzo 1993a; Ludwig, Meyer-Hofmeister & Ritter 1994; Hameury et al. 1998 for detailed calculations).

There is also a well-established class of close binaries, the so-called AM CVn stars, in which the donor star is thought to be a helium white dwarf (e.g. Warner 1995). Helium disks in these systems are subject to the same thermal ionization instability as hydrogen-rich disks, as shown by Smak (1983) and subsequent workers (Cannizzo 1984; Tsugawa & Osaki 1997; El-Khoury & Wickramasinghe 2000).

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Recently, the existence of a new class of close binaries, in which disks are not made of hydrogen or helium but instead metals such as O and Ne (because of the nature of the white dwarf donors), has been proposed (Schulz et al. 2001; Juett, Psaltis & Chakrabarty 2001). In our study of the properties of supernova fallback disks (predominantly made of metals; Menou, Perna & Hernquist 2001a,b), we showed that disks composed of pure C or O are also subject to the thermal ionization instability. We argued that accretion disks of any metal content should be subject to this instability as well.

In this *Letter*, we extend our work on metal disks to derive more precise global stability criteria. We then apply these results to the candidate metal disks in compact binaries, in an attempt to characterize their stability properties.

2. Local Thermal Structure

The thermal-viscous stability of gaseous, thin accretion disks around compact objects has been investigated extensively in the past. We follow a standard procedure here, similar to that employed to study the properties of fallback disks (Menou et al. 2001a). Because of the limited availability of metal opacities in the appropriate density and temperature ranges, our work is limited to C and O compositions only. The case of pure He is also considered for comparison with previous results.

The Rosseland-mean opacities are taken from the OPAL database (Iglesias & Rogers 1996)⁴. The opacities, at a specific mass density of 10^{-6} g cm⁻³, are shown as a function of temperature in Fig. 1, for the four compositions of interest: pure He (dash-dotted), pure C (dotted), pure O (dashed) and a C/O composition with a 40%–60% mass fraction (solid). The sudden opacity drop at temperatures $T \lesssim 10^4$ K, which corresponds to the recombination of the last free electron, is responsible in each case for the thermal ionization instability (Menou et al. 2001a). This temperature differs from composition to composition because of different ground state ionization potentials for each element. In particular, note that C dominates the opacity of the C/O composition at low temperatures (while O does at high temperatures). This is because C recombines at lower temperatures than O, and it implies that the stability properties of a disk with this C/O composition will be very similar to those of a disk made of pure C (see below).

The disk thermal equilibria are found by equating the local viscous dissipation rate Q^+ to the radiative cooling rate Q^- , where Q^- is a function of the disk opacity. We neglect X-ray irradiation when calculating the thermal equilibria (see discussion below). The thermal equilibria are calculated from an extended grid of detailed models for the disk vertical structure, for different values of the surface density Σ and the central temperature T_c , at a given radius R from the central object of mass M_1 (see Hameury et al. 1998 for details on the numerical technique employed).

⁴The OPAL database website is <http://www-phys.llnl.gov/Research/OPAL/>

Once a solution to the vertical structure (corresponding to a given Σ , T_c and R) is known, the disk effective temperature T_{eff} is uniquely determined. The equation of state adopted for all the compositions is that of a perfect gas with a monoatomic adiabatic index $\gamma = 5/3$. The lack of a detailed equation of state implies that vertical heat transport by convection, usually treated in the mixing length approximation, cannot be included in our calculations (see, e.g., Eq. [22] of Hameury et al. 1998). We note, however, that Gu, Vishniac & Cannizzo (2000) have argued for weak convection in thin accretion disks, because of the action of shearing and turbulent radial mixing.

Figure 2 shows thermal equilibrium curves (“S-curves”) thus obtained, in a surface density vs. effective temperature diagram. In each panel, the sections of the S-curves with negative slope are thermally and viscously unstable (see, e.g., Cannizzo 1993b and Lasota 2001 for reviews of the instability). For each composition, the thermal equilibrium solutions are shown for a different value of the viscosity parameter α , in order to guarantee that opacities are available in the range of density and temperature covered by the model. In the four panels of Fig. 2, the solid, dashed and dotted lines correspond to “S-curves” calculated at a radius $R = 2 \times 10^{10}$, 4×10^{10} and 6×10^{10} cm, respectively, from a central object of mass $M_1 = 1.4M_\odot$. (The calculation of only two S-curves for the He case was sufficient to test the consistency with previous results.)

The instability occurs at a characteristic effective temperature $T_{\text{eff,crit}}$ (where the slope in the S-curve changes from positive to negative), which is a function of the disk composition and the radius of interest. When vertical transport of heat by convection is not included, as is the case here (because of the simple equation of state used), the value $T_{\text{eff,crit}}$ is also function of the viscosity parameter α (see below). As expected from the C-dominated opacities at low temperatures, the S-curves for the C/O composition are very similar to those of the pure C case. Our results for the He case are in good agreement with previous work on He disks (e.g. Smak 1983, Tsugawa & Osaki 1997).

3. Global Stability Properties

The curves of thermal equilibrium can be used to derive a global stability criterion for the corresponding accretion disk. The relation $\dot{M} = 8\pi R^3 \sigma T_{\text{eff}}^4 / 3GM_1$ between the disk accretion rate and its effective temperature (e.g. Frank, King & Raine 1992) implies that a disk becomes thermally unstable if it locally accretes at a rate below the value corresponding to $T_{\text{eff,crit}}(R)$. The corresponding critical accretion rate is therefore obtained by fitting the turnover point of the “S-curve” at various radii for a given composition, as indicated by the dash-dotted line in Fig. 2.

For the four compositions of interest here, we find (after extrapolation to large α for the three metallic cases):

$$\text{He : } \dot{M}_{\text{crit}}^+(R) \simeq 5.9 \times 10^{16} m_1^{-0.87} R_{10}^{2.62} \alpha_{0.1}^{0.41} \text{ g s}^{-1}, \quad (1)$$

$$\text{C : } \dot{M}_{\text{crit}}^+(R) \simeq 1.3 \times 10^{16} m_1^{-0.74} R_{10}^{2.23} \alpha_{0.1}^{0.44} \text{ g s}^{-1}, \quad (2)$$

$$\text{O} : \dot{M}_{\text{crit}}^+(R) \simeq 5.0 \times 10^{16} m_1^{-0.68} R_{10}^{2.05} \alpha_{0.1}^{0.45} \text{ g s}^{-1}, \quad (3)$$

$$\text{C/O} : \dot{M}_{\text{crit}}^+(R) \simeq 1.2 \times 10^{16} m_1^{-0.74} R_{10}^{2.21} \alpha_{0.1}^{0.42} \text{ g s}^{-1}, \quad (4)$$

where m_1 is the mass of the central object in solar units, R_{10} is the radius of interest in units of 10^{10} cm and $\alpha_{0.1} = \alpha/0.1$. The scaling of $\dot{M}_{\text{crit}}^+$ with m_1 was deduced by noting that m_1 enters the problem only via the square of the Keplerian angular frequency, $\Omega_K^2 \propto m_1/R^3$, hence the direct proportionality to the scaling with radius (see Hameury et al. 1998 for the equations solved). We also have included in the above formulae the results of numerical explorations of the dependence of $\dot{M}_{\text{crit}}^+(R)$ on the viscosity parameter α (not explicitly shown in Fig. 2 for conciseness).⁵

These critical accretion rates do not differ strongly from the scaling $\dot{M}_{\text{crit}}^+(R) \simeq 9.3 \times 10^{15} m_1^{-0.89} R_{10}^{2.68} \text{ g s}^{-1}$ found by Hameury et al. (1998) in the solar composition case (for a viscosity parameter $\alpha = 0.1$). A disk of a given composition which satisfies everywhere $\dot{M}(R) > \dot{M}_{\text{crit}}^+(R)$ is ionized and thermally (as well as viscously) stable.

4. Applications

In what follows, we apply the stability criteria derived in §3 to a few specific systems. In each case, we adopt a viscosity parameter $\alpha = 0.1$ since there is empirical evidence from dwarf novae outbursts that this is the right order of magnitude for viscosity in a fully-ionized, MHD-turbulent thin disk (Smak 1999; Gammie & Menou 1998; Balbus & Hawley 1991; 1998).

4.1. Metal-Rich Disk in 4U 1626-67

Schulz et al. (2001) recently reported the *Chandra* detection of broad, double-peaked emission lines and strong photoelectric absorption edges of O and Ne in the low-mass X-ray binary pulsar 4U 1626-67. Based on this, the authors argued that the disk in this ultra-compact system (with $P_{\text{orb}} = 42$ min; Middleditch et al. 1981; Chakrabarty 1998) is probably fed by a C-O-Ne or O-Ne-Mg white dwarf of mass $0.02M_{\odot}$. The short orbital period and small mass ratio in 4U 1626-67 imply a disk outer radius $\sim 2 \times 10^{10}$ cm (Schulz et al. 2001; Wang & Chakrabarty 2001).

Assuming a mass $M_1 = 1.4M_{\odot}$ for the neutron star and a viscosity parameter $\alpha = 0.1$, we find that the mass-transfer rates below which the disk outermost regions in 4U 1626-67 become subject

⁵We have checked that, e.g. in the solar-composition case (for which a detailed equation of state was available), the dependence of $\dot{M}_{\text{crit}}^+$ on α nearly disappears when significant vertical heat transport by convection is allowed (see Fig. 2 of Menou et al. 2001a for a specific, quantitative comparison of stability in the presence and in the absence of convection). This result, which is confirmed by several previous vertical structure calculations (e.g. Cannizzo 1993b; Hameury et al. 1998; Tsugawa & Osaki 1997), shows that our poor understanding of the role of convection for vertical heat transport in thin disks is a significant source of uncertainty for the derived stability criteria.

to the thermal ionization instability are $\simeq 4.7 \times 10^{16} \text{ g s}^{-1}$ and $\simeq 1.6 \times 10^{17} \text{ g s}^{-1}$ for pure C and pure O compositions, respectively. We note that the various compositions discussed by Schulz et al. (2001) for the white dwarf donor are dominated by either C or O, with some contribution from Ne. The above estimates of critical mass-transfer rates for stability should therefore be relevant in most cases because the disk stability properties tend to be dominated by the element with the lowest recombination temperature, as shown in §2 and 3 (Ne recombines first, followed by O and then C at lower temperatures; see e.g. Mihalas et al. 1990). However, if Mg makes a significant contribution to the disk composition (a possibility suggested by Schulz et al. for an O-Ne-Mg white dwarf donor), the critical mass transfer rate could be even lower because Mg recombines at lower temperatures than C (we were unable to address the Mg case in detail because opacities were not available).

The above critical mass-transfer rates are between a factor a few and two orders of magnitude larger than the observationally-inferred value of $\sim 10^{16} \text{ g s}^{-1}$ and the theoretically-inferred value of $\sim 2 \times 10^{15} \text{ g s}^{-1}$ discussed by Schultz et al. (2001) for 4U 1626-67. Our work therefore suggests that the accretion disk in this system should be subject to the thermal ionization instability.⁶

4.2. Hydrogen-Poor Disks in Other Systems

Juett et al. (2001) propose that four other low-mass X-ray binaries (4U 0614+091, 2S 0918-549, 4U 1543-624, 4U 1850-087) are also ultra-compact binaries with low-mass, hydrogen-depleted donors. Only 4U 1850-087 has a known orbital period of 20.6 min (clearly making it an ultra-compact system), but Juett et al. argue that the three other systems may also have orbital periods smaller than 1 hr.

If this interpretation is correct (i.e. short orbital periods, low mass donors, helium- or metal-rich disks), we expect mass transfer driven by gravitational radiation at a rate similarly low as in 4U 1626-67 and disks equally subject to the thermal ionization instability.⁷ We note, however, that the knowledge of the binary orbital period is essential for the stability analysis because it largely determines the disk outer radius, which enters the stability criteria in Eqs. (1)–(4) with a large power.

4.3. Helium-Rich Disk in 4U 1820-30

The low-mass X-ray binary 4U 1820-30 is an ultra-compact system, with a 685 s orbital period, located in the globular cluster NGC 6624 (Stella, White & Priedhorsky 1987). The X-ray

⁶A similar conclusion is reached if the disk is assumed to have a solar composition.

⁷Again, the presence of a substantial amount of Mg in these disks could modify this conclusion.

burst properties of this system show that the donor star is a He white dwarf (Bildsten 1995). Given the short orbital period, the disk outer radius is $\lesssim 10^{10}$ cm and, according to Eq. (1), the critical mass-transfer rate below which the He disk would be subject to the thermal ionization instability is $\lesssim 4.4 \times 10^{16}$ g s $^{-1}$. The inferred X-ray luminosity of the system is $> 2 \times 10^{37}$ erg s $^{-1}$, however, implying an accretion rate in excess of 10^{17} g s $^{-1}$ (Bildsten 1995) and stability. This conclusion appears consistent with the inferred stability of the accretion rate in the system (Bildsten 1995), although the ~ 176 d low-amplitude luminosity cycle remains to be explained (Priedhorsky & Terrell 1984).

5. Discussion

We have calculated, as a function of radius, critical accretion rates below which disks become subject to the thermal ionization instability, for four specific hydrogen-poor compositions. We have applied these results to disks in several low-mass X-ray binaries with possibly Hydrogen-depleted donors and found that some of them could indeed be unstable.

We caution, however, that our results are subject to a number of uncertainties. We have already mentioned the uncertainties associated with the magnitude of convection in thin disks (our results correspond to the inefficient convection limit). We have also shown that the exact composition of the disk material is important because the stability properties are in general dominated by the element with the lowest ground state ionization potential (e.g. Mg for an O-Ne-Mg white dwarf). Finally, we have neglected the stabilizing effects of disk irradiation in our calculations (van Paradijs 1996; Dubus et al. 1999). This is not unreasonable given that all the systems discussed are thought to be ultra-compact, but we note that irradiation may affect the stability of disks extending beyond $10^9 - 10^{10}$ cm from the central neutron star, depending on their geometry (e.g. Dubus et al. 1999).

The usual outcome of the thermal ionization instability in low-mass X-ray binaries and dwarf novae is the development of large amplitude outbursts and subsequent long periods of quiescence. However, this outcome crucially depends on the efficiency of angular momentum transport (or equivalently the value of the viscosity parameter α) in the disk when it becomes neutral (in the sense that a value of α significantly smaller in the neutral disk than in the ionized disk is required to produce large amplitude outbursts; Smak 1984).⁸ While there are good reasons for α to be significantly reduced in a neutral, hydrogen-rich disk because of MHD turbulence decay (Gammie & Menou 1998; Menou 2000; Fleming, Stone & Hawley 2000), it may not be so in a hydrogen-poor disk.

⁸Several global numerical simulations have shown that, for similar values of α in the neutral and ionized phases, unstable disks experience only short, small amplitude luminosity variations (Smak 1984; Menou, Hameury & Stehle 1999).

Menou (2002) emphasizes the importance of dissociative recombination by molecular hydrogen as a “sink” for free electrons and therefore a “source” of large resistivity in neutral, hydrogen-rich disks. In disks lacking hydrogen, the decay of MHD turbulence may be reduced or even absent, depending on the physical state and chemistry of the gas in the neutral phase. In our view, this is one of the most interesting aspects of the physics of hydrogen-poor disks, in the sense that a differential study of the disk stability and variability properties in hydrogen-poor and hydrogen-rich systems may reveal important clues on the nature of viscosity in quiescent, neutral disks.

Acknowledgments

Support for this work was provided by NASA through Chandra Fellowship grant PF9-10006 awarded by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-39073. KM thanks the Center for Astrophysical Sciences at Johns Hopkins University for hospitality.

REFERENCES

- Balbus, S.A., & Hawley, J.F. 1991, *ApJ*, 376, 214
- Balbus, S.A., & Hawley, J.F. 1998, *Rev. Mod. Phys.*, 70, 1
- Bildsten, L. 1995, *ApJ*, 438, 852
- Cannizzo, J.K. 1984, *Nature*, 311, 443
- Cannizzo, J.K. 1993a, *ApJ*, 419, 318
- Cannizzo, J.K. 1993b, in Wheeler J.C., ed., *Accretion discs in Compact Stellar Systems* (World Scientific, Singapore), p. 6
- Chakrabarty, D. 1998, *ApJ*, 492, 342
- Dubus, G., Lasota, J.-P., Hameury, J.-M. & Charles, P. 1999, *MNRAS*, 303, 139
- El-Khoury, W. & Wickramasinghe, D. 2000, *A&A*, 358, 154
- Fleming, T.P., Stone, J.M. & Hawley, J.F. 2000, *ApJ*, 530, 464
- Frank, J., King, A.R. & Raine, D.J. 1992, *Accretion Power in Astrophysics* (Cambridge University Press, Cambridge)
- Gammie C.F., Menou K. 1998, *ApJ*, 492, L75
- Gu, P.-G., Vishniac, E.T. & Cannizzo, J.K. 2000, *ApJ*, 534, 380

- Hameury J.-M., Menou K., Dubus G., Lasota J.-P., Huré J.-M. 1998, MNRAS, 298, 1048
- Iglesias, C.A. & Rogers, F.J. 1996, ApJ, 464, 943
- Juett, A.M., Psaltis, D. & Chakrabarty, D. 2001, ApJ Lett., 560, L59
- Lasota, J.-P. 2001, New Astron. Rev., preprint
- Lewin, W.H.G., van Paradijs, J. & van den Heuvel, E.P.J. 1995, *X-ray Binaries* (Cambridge: Cambridge University Press)
- Ludwig, K., Meyer-Hofmeister, E. & Ritter, H. 1994, A&A, 290, 473
- Menou, K. 2000, Science, 288, 2022
- Menou, K. 2002, Proceedings of “The Physics of Cataclysmic Variables and Related Objects” (ASP Conference Ser.), eds. B. Gaensicke, K. Beuermann & K. Reinsch, astro-ph/0108287
- Menou, K., Hameury, J.-M., Stehle, R. 1999, MNRAS, 305, 79
- Menou, K., Perna, R. & Hernquist, L. 2001a, ApJ, 559, 1032
- Menou, K., Perna, R. & Hernquist, L. 2001b, ApJ, 554, L63
- Meyer, F., Meyer-Hofmeister, E. 1981, A&A, 104, L10
- Middleditch, J., Mason, K.O., Nelson, J.E. & White, N.E. 1981, ApJ, 244, 1001
- Mihalas, D., Hummer, D.G., Mihalas, B.W. & Dappen, W. 1990, ApJ, 350, 300
- Priedhorsky, W. & Terrell, J. 1984, ApJ, 284, L17
- Schulz, N.S. et al. 2001, ApJ, in press, astro-ph/0108208
- Stella, L., White, N.E. & Priedhorsky, W. 1987, ApJ, 312, L17
- Smak J. 1983, Acta Astron., 33, 333
- Smak J. 1984, Acta Astron., 34, 161
- Smak J. 1999, Acta Astron., 49, 391
- Tsugawa, M. & Osaki, Y. 1997, PASJ, 49, 75
- van Paradijs, J. 1996, ApJL, 464, L139
- Wang, Z. & Chakrabarty, D. 2001, ApJ, submitted
- Warner, B. 1995, *Cataclysmic variable stars* (Cambridge University Press, Cambridge)

Fig. 1.— Rosseland-mean opacities as a function of temperature, at a mass density of $10^{-6} \text{ g cm}^{-3}$, for pure Helium (dash-dotted), pure Carbon (dotted), pure Oxygen (dashed) and a Carbon/Oxygen composition with a 40%-60% mass fraction (solid). The sudden opacity drop at $T \lesssim 10^4 \text{ K}$ corresponds to the recombination of the last available free electron. Note the similarity of the C/O opacity to the Carbon one at low temperatures and to the Oxygen one at high temperatures.

Fig. 2.— Examples of thermal equilibrium curves (“S-curves”) for a thin accretion disk, shown in a surface density vs. effective temperature ($\Sigma - T_{\text{eff}}$) diagram. The curves correspond to a disk annulus located at 2×10^{10} cm (solid line), 4×10^{10} cm (dashed) or 6×10^{10} cm (dotted) from a central neutron star of mass $M_1 = 1.4M_{\odot}$. The four panels correspond to disks made of pure Helium (a), Carbon/Oxygen (40%-60% mass fraction; b), pure Carbon (c) and pure Oxygen (d). The value adopted for the viscosity parameter α and a fit to the critical effective temperature are shown in each panel.