Astronomy and Astrophysics 2021 vol.651

X-ray emission from magnetized neutron star atmospheres at low mass-accretion rates: I. Phase-averaged spectrum

Sokolova-Lapa E., Gornostaev M., Wilms J., Ballhausen R., Falkner S., Postnov K., Thalhammer P., Fürst F., García J.A., Shakura N., Becker P.A., Wolff M.T., Pottschmidt K., Härer L., Malacaria C.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

Recent observations of X-ray pulsars at low luminosities allow, for the first time, the comparison of theoretical models of the emission from highly magnetized neutron star atmospheres at low mass-accretion rates (M ≤ 1015 g s-1) with the broadband X-ray data. The purpose of this paper is to investigate spectral formation in the neutron star atmosphere at low á¹€ and to conduct a parameter study of the physical properties of the emitting region. We obtain the structure of the static atmosphere, assuming that Coulomb collisions are the dominant deceleration process. The upper part of the atmosphere is strongly heated by the braking plasma, reaching temperatures of 30-40 keV, while its denser isothermal interior is much cooler (~2 keV). We numerically solve the polarized radiative transfer in the atmosphere with magnetic Compton scattering, free-free processes, and nonthermal cyclotron emission due to possible collisional excitations of electrons. The strongly polarized emitted spectrum has a double-hump shape that is observed in low-luminosity X-ray pulsars. A low-energy "thermal"component is dominated by extraordinary photons that can leave the atmosphere from deeper layers because of their long mean free path at soft energies. We find that a high-energy component is formed because of resonant Comptonization in the heated nonisothermal part of the atmosphere even in the absence of collisional excitations. However, these latter, if present, affect the ratio of the two components. A strong cyclotron line originates from the optically thin, uppermost zone. A fit of the model to NuSTAR and Swift/XRT observations of GX 304-1 provides an accurate description of the data with reasonable parameters. The model can thus reproduce the characteristic double-hump spectrum observed in low-luminosity X-ray pulsars and provides insights into spectral formation.

http://dx.doi.org/10.1051/0004-6361/202040228

Keywords

Magnetic fields, Methods: numerical, Polarization, Radiative transfer, Stars: neutron, X-rays: binaries

References

[1] Adler, S. L. 1971, Ann. Phys., 67, 599
[2] Alexander, S. G., Meszaros, P., & Bussard, R. W. 1989, ApJ, 342, 928

[3] Alme, M. L., & Wilson, J. R. 1973, ApJ, 186, 1015
[4] Astropy Collaboration (Robitaille, T. P., et al.) 2013, A&A, 558, A33
[5] Astropy Collaboration (Price-Whelan, A. M., et al.) 2018, AJ, 156, 123
[6] Auer, L. 1967, ApJ, 150, L53
[7] Basko, M. M., & Sunyaev, R. A. 1975, A&A, 42, 311
[8] Basko, M. M., & Sunyaev, R. A. 1976, MNRAS, 175, 395
[9] Becker, P. A., & Wol, M. T. 2007, ApJ, 654, 435
[10] Becker, P. A., Klochkov, D., Schönherr, G., et al. 2012, A&A, 544, A123
[11] Bellm, E. C., Fürst, F., Pottschmidt, K., et al. 2014, ApJ, 792, 108
[12] Burnard, D. J., Arons, J., & Klein, R. I. 1991, ApJ, 367, 575
[13] Bussard, R. W. 1980, ApJ, 237, 970
[14] Bussard, R. W., Alexander, S. B., & Meszaros, P. 1986, Phys. Rev. D, 34, 440
[15] Bykov, A. M., & Krasil'Shchikov, A. M. 2004, Astron. Lett., 30, 309
[16] Cash, W. 1979, ApJ, 228, 939
[17] Ceccobello, C., Farinelli, R., & Titarchuk, L. 2014, A&A, 562, A99
[18] Daugherty, J. K., & Harding, A. K. 1986, ApJ, 309, 362
[19] Davidson, K. 1973, Nat. Phys. Sci., 246, 1
[20] Deufel, B., Dullemond, C. P., & Spruit, H. C. 2001, A&A, 377, 955
[21] Doroshenko, V., Santangelo, A., Kreykenbohm, I., & Doroshenko, R. 2012, A&A, 540, L1
[22] Dove, J. B., Wilms, J., & Begelman, M. C. 1997, ApJ, 487, 747
[23] Farinelli, R., Ferrigno, C., Bozzo, E., & Becker, P. A. 2016, A&A, 591, A29
[24] Feautrier, P. 1964, SAO Special Rep., 167, 80
[25] Ge, M. Y., Ji, L., Zhang, S. N., et al. 2020, ApJ, 899, L19
[26] Gnedin, Y. N., Pavlov, G. G., & Shibanov, Y. A. 1978, Sov. Astron. Lett., 4, 117
[27] Gornostaev, M. I. 2021, MNRAS, 501, 564
[28] Harding, A. K., Meszaros, P., Kirk, J. G., & Galloway, D. J. 1984, ApJ, 278, 369
[29] Herold, H. 1979, Phys. Rev. D, 19, 2868
[30] Ho, W. C. G., & Lai, D. 2003, MNRAS, 338, 233
[31] Houck, J. C., & Denicola, L. A. 2000, in Astronomical Data Analysis Software and Systems IX, eds. N. Manset, C. Veillet, & D. Crabtree, ASP Conf. Ser., 216, 591
[32] Hua, X.-M., & Titarchuk, L. 1995, ApJ, 449, 188
[33] Hunter, J. D. 2007, Comput. Sci. Eng., 9, 90
[34] Jaisawal, G. K., Naik, S., & Epili, P. 2016, MNRAS, 457, 2749
[35] Kaastra, J. S., & Bleeker, J. A. M. 2016, A&A, 587, A151
[36] Kirk, J. G., & Galloway, D. 1982, J. Plasma Phys., 24, 339
[37] Kirk, J. G., & Meszaros, P. 1980, ApJ, 241, 1153
[38] Klochkov, D., Doroshenko, V., Santangelo, A., et al. 2012, A&A, 542, L28
[39] Kühnel, M., Rothschild, R. E., Okazaki, A. T., et al. 2017a, MNRAS, 471, 1553
[40] Kühnel, M., Fürst, F., Pottschmidt, K., et al. 2017b, A&A, 607, A88
[41] Lai, D. 2001, Rev. Mod. Phys., 73, 629
[42] Lamb, F. K., Pethick, C. J., & Pines, D. 1973, ApJ, 184, 271
[43] Langer, S. H., & Rappaport, S. 1982, ApJ, 257, 733
[44] Lewin, W. H. G., Clark, G. W., & Smith, W. B. 1968a, ApJ, 152, L49
[45] Lewin, W. H. G., Clark, G. W., & Smith, W. B. 1968b, Nature, 220, 249
[46] Lutovinov, A., Tsygankov, S., Molkov, S., et al. 2021, ApJ, 912, 17
[47] Lyubarskii, Y. É. 1988a, Astrophysics, 28, 106
[48] Lyubarskii, Y. É. 1988b, Astrophysics, 28, 253
[49] Malacaria, C., Klochkov, D., Santangelo, A., & Staubert, R. 2015, A&A, 581, A121
[50] Malacaria, C., Kollatschny, W., Whelan, E., et al. 2017, A&A, 603, A24
[51] Manousakis, A., Beckmann, V., Bianchin, V., et al. 2008, ATel, 1613
[52] McClintock, J. E., Ricker, G. R., & Lewin, W. H. G. 1971, ApJ, 166, L73

[53] McClintock, J. E., Rappaport, S. A., Nugent, J. J., & Li, F. K. 1977, ApJ, 216, L15
[54] Meszaros, P., & Nagel, W. 1985a, ApJ, 298, 147
[55] Meszaros, P., & Nagel, W. 1985b, ApJ, 299, 138
[56] Meszaros, P., & Ventura, J. 1978, Phys. Rev. Lett., 41, 1544
[57] Meszaros, P., & Ventura, J. 1979, Phys. Rev. D, 19, 3565
[58] Meszaros, P., Harding, A. K., Kirk, J. G., & Galloway, D. J. 1983, ApJ, 266, L33
[59] Meszaros, P., Pavlov, G. G., & Shibanov, I. A. 1989, ApJ, 337, 426
[60] Mihalas, D. 1978, Stellar Atmospheres (San Francisco: W. H. Freeman)
[61] Miller, G. S., Salpeter, E. E., & Wasserman, I. 1987, ApJ, 314, 215
[62] Miller, G., Wasserman, I., & Salpeter, E. E. 1989, ApJ, 346, 405
[63] Mushtukov, A. A., Tsygankov, S. S., Serber, A. V., Suleimanov, V. F., & Poutanen, J. 2015, MNRAS, 454, 2714
[64] Mushtukov, A. A., Nagirner, D. I., &Poutanen, J. 2016, Phys. Rev. D, 93, 105003
[65] Mushtukov, A. A., Suleimanov, V. F., Tsygankov, S. S., & Portegies Zwart, S. 2021, MNRAS, 503, 5193
[66] Nagel, W. 1980, ApJ, 236, 904
[67] Nagel, W. 1981, ApJ, 251, 288
[68] Nelson, R. W., Salpeter, E. E., & Wasserman, I. 1993, ApJ, 418, 874
[69] Nelson, R. W., Wang, J. C. L., Salpeter, E. E., & Wasserman, I. 1995, ApJ, 438, L99
[70] Oliphant, T. E. 2006, A Guide to NumPy (USA: Trelgol Publishing), 1
[71] Parkes, G. E., Murdin, P. G., & Mason, K. O. 1980, MNRAS, 190, 537
[72] Pietsch, W., Oegelman, H., Kahabka, P., Collmar, W., & Gottwald, M. 1986, A&A, 163, 93
[73] Postnov, K. A., Gornostaev, M. I., Klochkov, D., et al. 2015a, MNRAS, 452, 1601
[74] Postnov, K. A., Mironov, A. I., Lutovinov, A. A., et al. 2015b, MNRAS, 446, 1013
[75] Priedhorsky, W. C., & Terrell, J. 1983, ApJ, 273, 709
[76] Rothschild, R. E., Kühnel, M., Pottschmidt, K., et al. 2017, MNRAS, 466, 2752
[77] Rouco Escorial, A., van den Eijnden, J., & Wijnands, R. 2018, A&A, 620, L13
[78] Schönherr, G., Wilms, J., Kretschmar, P., et al. 2007, A&A, 472, 353
[79] Schwarm, F.-W., Ballhausen, R., Falkner, S., et al. 2017, A&A, 601, A99
[80] Shapiro, S. L., & Salpeter, E. E. 1975, ApJ, 198, 671
[81] Sina, R. 1996, PhD Thesis, University of Maryland, USA
[82] Soel, M., Ventura, J., Herold, H., Ruder, H., & Nagel, W. 1983, A&A, 126, 251
[83] Staubert, R., Trümper, J., Kendziorra, E., et al. 2019, A&A, 622, A61
[84] Suleimanov, V. F., Poutanen, J., & Werner, K. 2018, A&A, 619, A114
[85] Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 500, 167
[86] Sykes, J. B. 1951, MNRAS, 111, 377
[87] Tavella, D., & Randall, C. 2000, Pricing Financial Instruments: The Finite Di_erence Method (New York: Wiley)
[88] Tsygankov, S. S., Rouco Escorial, A., Suleimanov, V. F., et al. 2019a, MNRAS, 483, L144
[89] Tsygankov, S. S., Doroshenko, V., Mushtukov, A. E. A., et al. 2019b, MNRAS, 487, L30
[90] Turolla, R., Zampieri, L., Colpi, M., & Treves, A. 1994, ApJ, 426, L35
[91] Ventura, J. 1979, Phys. Rev. D, 19, 1684
[92] Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJ, 465, 487
[93] Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nat. Methods, 17, 261
[94] Vybornov, V., Klochkov, D., Gornostaev, M., et al. 2017, A&A, 601, A126
[95] Wang, Y. M. 1996, ApJ, 465, L111
[96] Wang, Y. M., & Frank, J. 1981, A&A, 93, 255
[97] Wang, J. C. L., Wasserman, I. M., & Salpeter, E. E. 1988, ApJS, 68, 735
[98] Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
[99] Wilms, J., Nowak, M. A., Pottschmidt, K., et al. 2006, A&A, 447, 245
[100] Wol, M. T., Becker, P. A., Gottlieb, A. M., et al. 2016, ApJ, 831, 194
[101] Yamamoto, T., Sugizaki, M., Mihara, T., et al. 2011, PASJ, 63, S751
[102] Yamamoto, T., Mihara, T., Sugizaki, M., et al. 2014, PASJ, 66, 59
[103] Zel'dovich, Y. B., & Shakura, N. I. 1969, Sov. Astron., 13, 175