Final Report on Research Conducted at MIT
by Wei Cui

My group, in close collaboration with Dr. Zhang's group at University of Alabama-Huntsville, have been systematically analyzing and re-analyzing a substantial amount of archival data from previous and ongoing X-ray missions, in order to study possible relativistic effects around stellar-mass black holes and neutron stars. Our effort has been focused primarily on the data from the Rossi X-ray Timing Explorer. We carefully studied interesting quasi-periodic X-ray variability in newly discovered black hole candidates (XTE J1859+226 and XTE J1550-564), which, as we had proposed earlier, could be caused by general relativistic process (e.g., frame dragging) around the central black hole. We also discovered an intriguing temporal correlation between X-ray photons at different energies that is associated with the quasi-periodic signals of interest. The results provided new insights into the physical origin of the phenomena. Furthermore, we studied the spectral lines of black hole candidates which provide another avenue for studying general relativistic processes around black holes. The lines may originate in the relativistic jets (which could be powered by the spin of the black hole) or in the disk around the black hole, as in the cases of 4U 1630-47 and GX 339-4 (two well-known black hole candidates), and may thus be distorted or shifted due to relativistic effects. Of course, neutron star systems were not forgotten either. After examining the properties of newly discovered fast quasi-periodic variability (at kiloHertz) associated with such systems, we proposed a relativisitic model to explain the origin of the signals. We have also started to use new great observatories in orbit (such as Chandra and XMM-Newton) to observe the sources that are of interest to us. Finally, interesting results were also been obtained from our collaborations with other groups who are interested in some of the same objects. Such collaborative efforts have greatly enhanced the project and will likely continue in the future.

RELEVANT PUBLICATIONS
Peer-Reviewed Papers:

1) ``Evolution of the Iron K-alpha Emission Line in the Black Hole Candidate GX339-4 During an Outburst Decay Phase," Feng, Y., Zhang, S.N., Chen, W., and Cui, W. 2000, ApJ, submitted
2) ``Peculiar Extended X-ray Emission around the ``Radio-Loud" Black Hole Candidate 1E1740.7-2942," Cui, W., Schulz,~N.~S., Baganoff,~F.~K., Bautz,~M.~W., Doty,~J.~P., Garmire,~G.~P., Mirabel,~I.~F., Ricker,~G.~R., Rodr\'\i guez,~L.~F., and Taylor,~S.~C. 2000, ApJ, submitted.
3) ``The correlated intensity and spectral evolution of Cyg X-1 during the state transition," Wen,~L., Cui, W., and Bradt,~H.~V. 2000, ApJ Letter, submitted.
4) ``Complete RXTE Spectral Observations of the Black Hole X-ray Nova XTE J1550-564," Sobczak,~G.~J., McClintock,~J.~E., Remillard,~R.~A., Cui, W., Levine,~A.~M., Morgan,~E.~H., Orosz,~J.~A., and Bailyn,~C.~D. 2000, ApJ, 544, in press.

5) ``The Chandra X-ray Observatory Resolves the X-ray Morphology and Spectra of a Jet in PKS 0637-752,'' Chartas,~G., Worrall,~D.~M., Birkinshaw,~M., Cresitello-Dittmar,~M., Cui,~W., Ghosh,~K.~K., Harris,~D.~E., Hooper,~E.~J., Jauncey,~D.~L., Kim,~D.-W., Lovell,~J., Marshall,~H.~L., Mathur,~S., Schwartz,~D.~A., Tingay,~S.~J., Virani,~S.~N., and Wilkes,~B.~J. 2000, ApJ, in press.
6) ``The Timing Evolution of 4U 1630-47 during its 1998 Outburst,'' Dieters,~S.~W., Belloni,~T., Kuulkers,~E., Woods,~P., Cui,~W., Zhang,~S.~N., Chen,~W., van der Klis,~M., van Paradijs,~J., and Lewin,~W.~H.~G. 2000, ApJ, in press.
7) ``The X-ray transient XTE J1118+480: Multiwavelength observations of a low-state mini-outburst,'' Hynes,~R.~I, Mauche,~C.~W., Haswell,~C.~A., Shrader,~C.~R., Cui,~W., and Chaty,~S. 2000, ApJ Letters, 539, L37.
8) ``Discovery of High-Frequency QPOs in Black Hole Candidate XTE J1859+226'', Cui,~W., Shrader,~C.~R., Haswell,~C.~A., and Hynes,~I.~H. 2000, ApJ Letters, 535, L123.
9) ``On the Disappearance of Kilohertz Quasi-Periodic Oscillations at a High Mass Accretion Rate in Low-Mass X-ray Binaries'', Cui,~W. 2000, ApJ Letters, 534, L31.
10) ``Correlations Between Low Frequency QPOs and Spectral Parameters in XTE J1550-564 and GRO J1655-40,'' Sobczak,~G.~J., McClintock,~J.~E., Remillard,~R.~A., Cui, W., Levine,~A.~M., Morgan,~E.~H., Orosz,~J.~A., and Bailyn,~C.~D. 2000, ApJ, 531, 537.
11) ``Three-Layered Atmospheric Structure in Accretion Disks Around Stellar-Mass Black Holes,'' Zhang,~S.~N., Cui,~W., Chen,~W., Yao,~Y., Zhang,~X., Sun,~X., Wu,~X.-B., and Xu,~H. 2000, Science, 287, 1239.
12) ``Phase Lag and Coherence Function of X-ray emission from Black Hole Candidate XTE J1550-564,'' Cui,~W., Zhang,~S.~N., and Chen,~W. 2000, ApJ Letters, 531, L45.
13) ``Evidence for Doppler-Shifted Iron Emission Lines in Black Hole Candidate 4U~1630-47,'' Cui, W., Chen~W., and Zhang,~S.~N. 2000, ApJ, 529, 952.
14) ``Orbital Modulation of X-rays from Cygnus X-1 in its Hard and Soft States,'' Wen, L., Cui, W., Levine, A. M., and Bradt, H. V. 1999, ApJ, 525, 968.
15) ``Phase Lags of QPOs in Microquasar GRS 1915+105,'' Cui, W. 1999, ApJ Letters, 524, L59.
16) ``Strong Aperiodic X-ray Variability and Quasi-Periodic Oscillation in X-ray Nova XTE J1550-564,'' Cui, W., Chen, W., Zhang, S. N., \& Morgan, E. H. 1999, ApJ Letters, 512, L43.

Conference Papers:
1) ``Relativistic Processes in Micro-quasars,'' Cui, W. 1999, invited review, Proceedings of The Frascati Workshop on ``Multifrequency Behaviour of High Energy Cosmic Sources'', Vulcano, Italy, May 24-29, 1999.