THE WARM-HOT INTERGALACTIC MEDIUM

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Annual Report

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This grant is associated to a 5-year LTSA grant, on "Studying the Largest Reservoir of Baryons in the Universe: The Warm-Hot Intergalactic Medium". The first year of work within this program has been very rich, and has already produced several important results, as detailed below. Table 2 of our original proposal justification, listed the planned year-by-year program, divided into two sub-fields: (A) the study of the z=0 (or Local Group WHIM) system, and (B) the study of the z > 0 (i.e. intervening WHIM) systems. For each of the two sub-fields we had planned to analyze, in the first year, a number of archival (Chandra, XMM and FUSE) and new (if observed) sightlines. Moreover, the plan for the z=0 system included the search for new interesting sightlines in the public archives, and the start of a study of Galactic sightlines. We have accomplished all these tasks.

We used the Chandra-LETG (AO4) data from our two highly successful "Target of Opportunity Observations (TOO)" of the nearby (z=0.03) blazar Mkn 421, together with our FUSE data (again a TOO) and the archival HST-GHRS data of the same object, to: (a) discover the first two intervening (i.e. z>0) Warm-Hot Intergalactic Medium (WHIM) filaments; (b) estimate, for the first time, the number density (i.e. number of WHIM filaments per unit redshift) of OVII WHIM filaments, and, most importantly, (c) to estimate, for the first time, the cosmological mass density of OVII WHIM filaments in the Local Universe. Estimates (b) and (c) turned out to be fully consistent with theoretical predictions and with the number of missing baryons in the Universe, although the errors are still very large, due to the small number of yet detected systems (two). We were also able to estimate, for the first time, the metallicity (i.e. Z>2 elements, compared to H) of these systems, which turned out to be of the order of a tenth of solar. Relative metallicities (i.e. O/N, O/Ne, O/C), could also be estimated for the first time in the WHIM. Metallicity measurements are extremely important because, on one side can be used to refine theoretical calculations, which are now based on very poor guesses on the degree of enrichment of the IGM, and, on the other hand, provide invaluable hints on the main mechanisms with which the IGM has been metal-fed in the past.

These results have been recently summarized in 3 different refereed papers. The first paper will be published in one of the January/February 2005 issues of the journal Nature, and concerns the first estimate of the Cosmological Mass measurements in the WHIM, offering the solution to the problem of the 'missing baryons' in the Local Universe. The second paper, describes in detail the reduction and analysis of the Chandra-LETG data of Mkn 421, and present the discovery of the two absorption systems at z=0.011 and z=0.027, together with a deep discussion of all possible interpretations. This paper has been submitted to the ApJ and has already received a positive referee report. It will be re-submitted shortly to the journal. Finally, a third refereed paper has been recently accepted by the ASR, and contains (a) a summary of the results on the 2 intervening WHIM systems along the line of sight to Mkn 421, as well as (b) the first preliminary results on the detections of two more WHIM systems along the line of sight to 1ES 1028+511 (z=0.361; our first Chandra-LETG AO5 TOO), and (c) a discussion on the comparison between gratings and calorimeters, to detect WHIM filaments in future, high-throughput, X-ray missions.

At redshift close to zero (i.e. Local Group WHIM), we have again used the unique data of Mkn 421, both in the X-ray and in the FUV, to study in great detail the z=0 ionized absorption system along the line of sight to this object. A graduate student at Ohio State University, R. Williams, supervised by one of the Co-I of our LTSA proposal, Dr. S. Mathur, has analyzed the 14 absorption lines from highly ionized metals, present in the Chandra and FUSE spectra of Mkn 421. Thanks to the very high signal to noise of these data, we were able, for the first time, to estimate the Doppler parameter of the OVII absorber in the X-ray, and so to rule out the identification of this absorber with the low-velocity OVI absorber imprinting a strong absorption line in the FUV spectrum and produced in the thick disk of our Galaxy. Moreover, the comparison of the X-ray line ratios with opportune models (produced by one of our Co-Is, Y. Krongold), has allowed us to establish that the X-ray absorber must be very tenuous (ne < 1e-4 cm-3), so further confirming the extragalactic origin of the X-ray absorber. These important results have been summarized in a paper that has been recently submitted to the ApJ.

Finally, we are currently working on the data reduction and analysis of a Chandra-LETG observation (of which the PI of this LTSA proposal, is a Co-I) of the High-Mass X-ray binary LMC-X3, which will tell us whether highly ionized X-ray absorption with the same properties as those seen along extragalactic sightlines, is present along this line of sight, within the first few tens of kpc from the Galaxy's center.

The analysis of these data, led by the PI of the Chandra observation (T. Fang), is still preliminary and so no conclusions can be drawn at this time.

During the year 2004, the above results have been presented by the PI at several conferences and/or seminars at international institutes: (a) a seminar at the Instituto de Astronomia of the Universidad National Autonoma de Mexico (Mexico City, November 2004); (b) a Colloquium at the Department of Astronomy of the Ohio State University (Columbus, OH, November 2004); (c) a seminar at the "Osservatorio Astronomico di Palermo" (Palermo, September 2004) (d) "The Environments of Galaxies" conference (Crete, August 2004); (e) The COSPAR Symposium E1.2 (Paris, June 2004); (f) The IAU Symposium No. 195 (Turin, May 2004); (g) The special session of the AAS conference of January 2004 (Atlanta, GE, January 2004); (h) The Aspen Winter Conference on "The Large-scale Distribution of Mass & Light in the Universe" (Aspen, CO, January 2004).

Very recently (in the last couple of months) we have started looking systematically in the Chandra and XMM archives, to study the z=0 systems along a number of lines of sight. A graduate student from the UNAM (Mexico City), is working with me on this project, since November 2004. We have already selected a sample of 12 different sightlines. These include the high signal to noise sightlines to Mkn 421, 3C 273, PKS 2155-304, NGC 5548, 1ES 1028+511 (proprietary: our data), 1ES 0502+675 (proprietary: our data). For all these objects we plan to produce single, detailed papers on the z=0 systems along these lines of sight (and others on possible z > 0 WHIM systems). These and all the other selected sightlines, instead, will be included in a summary paper on the physical and spatial properties of the z=0 system.

Finally, I would like to end this report, listing the new observing time that we have been already awarded with Chandra, XMM and FUSE, to further investigate on these topics, during the next four coming years of this program: (a) a 350 ks Large Program has been approved in Chandra-AO6 (PI: F. Nicastro), to observe two more blazar sightlines, exploiting the highly successful TOO strategy that led us to the discovery of the first WHIM filaments; (b) a 300 ks Large Program has been approved in XMM-Newton AO4 (PI: F. Nicastro), to integrate, on one of the high-z sightlines observed with Chandra (in AO5) and along with we already discovered at least 2 new WHIM systems. (c) 200 ks have been approved with FUSE, to follow up on the lines of sight observed with Chandra and/or XMM, to complement the X-ray data with the invaluable information provided by the OVI(lambda=1032A) transition present in the FUV band.