SUMMARY OF RESEARCH

My research is in the fields of (1) low redshift intergalactic medium, and (2) quasars and AGNs. I discuss some of my results below.

Major Accomplishments:

1. The Intergalactic Medium

   - Initiated the study of the low redshift warm-hot intergalactic medium (WHIM) with X-ray observations.
     - With Chandra observations, provided the first direct evidence of the WHIM predicted by the leading cosmological theories.
     - Provided evidence of the Local Group IGM.
     - Made the first direct measurements to account for the "missing" low redshift baryons.

2. Quasars and the Active Galactic Neclei

   - Solved the longstanding problem of associated absorption in UV and in X-rays.
     - After six years of controversy, our unified X-ray/UV absorber model is found to be correct by high resolution *Chandra* and *HST* -STIS observations.
     - This work has given rise to new and promising attempts to explain the whole phenomenology of the intimate AGN environment.
   - Solved the mystery of weak X-ray flux from broad absorption line quasars.
     - BALQSOs are found to be intrinsically X-ray bright, but highly absorbed quasars.
     - Kinetic energy carried out in the outflow is found to be comparable to the luminosity of quasars, changing the physical picture and straining existing models.
   - Provided new insights to the narrow line Seyfert 1 phenomenon.

  - NLS1 galaxies are likely to be AGNs in early evolutionary stage.
  - As such, they appear to be low-redshift, low-luminosity analogues of high redshift quasars.
  - NLS1s appear to have high gas phase metallicities, suggesting co-evolution of galaxies and their active nuclei.
- Provided evidence for accretion growth of black holes.
  - Highly accreting AGNs seem to occupy a separate region in the black-hole mass–Bulge mass relationship of normal galaxies.
  - These observations suggest that black holes grow by accretion in well formed bulges and approach the $M_{BH} - \sigma$ relation asymptotically over time.

1 The Warm-Hot Interglactic Medium

Recent estimates of the primordial deuterium abundance, combined with the theory of big bang nucleosynthesis (BBN), imply a baryon density parameter $\Omega_b \approx 0.04 h_{70}^{-2}$. At high redshift, it appears that most of these baryons reside in the diffuse intergalactic medium (IGM) and have been detected by Lyα forest absorption in background quasars. However, the census of baryons at low redshift is much more uncertain. The baryons in the stellar and gaseous components of galaxies add up to $\Omega_b \approx 0.004 h_{70}^{-1}$, a factor of ten below the BBN abundance. The plasma detected by X-ray emission in groups and clusters makes a similar contribution to Ω_b. It therefore appears that the main reservoir of low redshift baryons has not yet been detected.

Hydrodynamic cosmological simulations predict that a large fraction of the low redshift baryons should still reside in a diffuse IGM, analogous to the medium that produces the high-z Lyα forest. However, the IGM is harder to probe at low redshift because the density of the universe is lower and because much of the gas has been shock heated to temperatures of $\sim 10^5 - 10^7$K, where it produces very little hydrogen absorption. This gas is too diffuse and too cool to produce substantial X-ray emission. The most promising, and perhaps the only, way to trace this component is via the "X-ray forest" of high-excitation metal lines. If the theoretical models of this low redshift baryon reservoir component are correct, then the dominant ionization state should be OVII: Helium-like Oxygen.

For the first time in X-ray astronomy, the *Chandra* and XMM gratings have enough resolution to study the narrow, intervening absorption lines in quasar spectra. We have initiated a program to map the low-redshift IGM in the high ionization metal absorption lines. As a first step, we observed H1821+643, the brightest X-ray quasar with known intervening OVI systems. These were difficult observations and the results were tantalizing. We found that photoionization by metagalactic UV and X-ray background contributes substantially to the ionization balance of the WHIM. The marginal detections and upper limits provided useful constraints on the physical conditions in the WHIM. Our new strategy involves observing blazars in exceptionally high state. This proved very successful as we have robust detections of 2 systems through OVII, OVIII, CVI and NeIX absorption lines. We find the physical conditions and number density of systems to match the theoretical predictions. Indeed, the X-ray observations seem to probe the diffuse IGM with overdensities $\delta \sim 50$. If the line of sight to Mrk 421 is representative of the large scale distribution of WHIM, then we can claim that the missing baryons have been found.

As an added bonus, we also get to probe the Local Group IGM, through the z=0 absorption systems. The first "tree" in the X-ray forest was found with the z=0 OVII, OVIII and NeIX absorption lines towards PKS 2155-304. Physical conditions in the absorbing medium, together with the non-detection of emission, imply that we are probing the diffuse IGM, and not some hot clouds in the Galactic halo. The distribution in sky of the OVI high velocity clouds suggests local group origin, but this result needs to be tested further with better data and modeling.

We have several upcoming observations aimed at mapping the local group z=0 and intervening absorption systems along different lines of sight.

2 X-ray/UV Absorbing Outflows in AGNs

The "feedback" from AGNs has become a key notion in understanding many phenomena including heating of the intracluster medium, the "proximity effect" near galaxies, and the enriching and ionizing of the intergalctic medium.

For AGN astronomers, however, the outflows have been important in their own right, for understanding large scale mass, energy and momentum transports, their relation to the quasar power source and their interaction with the host galaxy.

Associated absorption lines in the optical/ultraviolet spectra of quasars, present in $\sim$10% of quasars, potentially provide strong probes of circumnuclear material. About 50% of Seyfert galaxies also show associated absotption lines. Their physical nature, however, was an unsolved problem for some 20 years.

This situation changed with quasi-simultaneous observations of the quasar 3C351 with *ROSAT* and *HST* . The X-ray spectrum revealed the presence of a warm absorber showing K-edge due to OVII or OVIII (paper # 4). The UV spectrum showed strong, associated, high-ionization absorption lines including OVI $\lambda\lambda 1031, 1037$. Through detailed modeling we find an excellent match between the X-ray and UV absorber properties (paper # 6). The combination of both X-ray and UV datasets allows strong constraints to be placed upon the physical conditions of the absorber. In 3C351 we find that the absorber has well determined properties which describe a component of nuclear material not previously recognized: highly ionized, outflowing, low density, high column density material situated outside the broad emission line region.

Through a series of papers we extended the 3C351 results, with studies of more sources and better modeling. These results open up the possibility that this "unified picture" of X-ray/UV outflows is quite general. It suggests that a wide range of associated absorbers may in fact be related through a continuum of properties like the column density, ionization parameter, distance from the continuum source, and the outflow velocity (see reviews in Conference Proceedings # 4 and # 20).

Understanding of the physical properties of the absorber allowed us ask astrophysical questions about the geometry and kinematics of the absorbing outflow. We found that the outflow is likely to be edge-on, carrying kinetic energy a large fraction of the bolometric luminosity of the AGN (paper # 10).

High resolution X-ray observations with Chandra and XMM confirmed and extended our results. We have developed a new photoionization model, PHASE, to understand the wealth of data provided by the grating spectra. So far we have applied the code to model the spectra of two sources which has yielded precise measurements of the physical conditions in the AGN outflows.

3 Broad Absorption Line Quasars

BALQSOs show associated absorption lines with outflow velocities up to 0.1c – 0.2c, a major challenge to theoretical models. However, physical conditions in the absorbing gas in the BALQSOs are poorly determined from optical/UV studies alone. This is because only a few, usually saturated, lines are measured, yielding lower limits to column densities for a few ions but little information on the ionization state. If, as in the associated absorbers described above, there is X-ray absorption as well as optical and UV, then the combined analysis would allow us to understand the BALQSOs better.

This, however, has been difficult since the BALQSOs are elusive X-ray sources and so are essentially unconstrained in their X-ray properties. Are they intrinsically X-ray quiet? Or is it strong absorption that makes them look faint?

Through a series of papers we showed that BALQSOs are X-ray weak as a class, and that a large $\boldsymbol{\alpha_{ox}}$ is a defining characteristic of BALQSOs. We found that strong absorption is the cause and in some cases the absorbers are even Compton thick. The inferred column densities are *at least* an order of magnitude larger than those estimated from optical/UV spectra alone, implying a large mass outflow rate and energy outflow rate a large fraction of the bolometric luminosity of the quasar.

Recent *Chandra* results have shown that low-ionization BALQSOs are even more X-ray weak than high-ionization BALQSOs. The former may be intrinsically weaker and perhaps represent an early evolutionary phase of quasars.

4 Narrow-Line Seyfert 1 Galaxies

Through a series of papers, we investigated the peculiar continuum and emission line properties of NLS1s with optical, UV and X-ray observations (papers ????). It is now well established that NLS1s lie at one extreme end of the eigenvector 1 of AGNs, with narrow emission lines, large Hβ/[OIII] ratio, strong FeII emission, and steep soft- as well as hard-X-ray spectra. They also exhibit rapid, large amplitude variability. The well accepted paradigm for NLS1s is that they have relatively small black hole masses and large accretion rates compared to their broad-line cousins.

Taking this as our working hypothesis, one can then ask "what determines the accretion rate in an AGN?" I have proposed that NLS1 galaxies might be active galaxies in the making and as such may represent a crucial early phase in the evolution of galaxies and active galaxies. This would make them low redshift, low luminosity analogues of the high redshift quasars (papers #28, ??). This hypothesis has gained support in the literature with over 60 citations in last four years.

Perhaps my most important find on NLS1s is that they do not follow the $M_{BH} - -\sigma$ relation (the relation between the black hole mass and host galaxy bulge velocity dispersion) of normal galaxies and some broad line Seyfert galaxies. We find that NLS1s lie below the $M_{BH} - -\sigma$ relation implying that their black holes are still growing. We propose that accretion onto a BH is highest in the beginning and dwindles with time. BHs grow significantly by accretion in luminous phase, and approach the $M_{BH} - -\sigma$ relation asymptotically. These observations challenge many theories attempting to explain the $M_{BH} - -\sigma$ relation. We are making new observations to confirm and extend this result.

Our recent *Chandra* observations of NLS1s selected from SDSS show that NLS1s are a mixed bag: some are soft X-ray steep, but some are not. Those with steep spectra are highly accreting and FeII bright, but others are not. These results have profound implications for the meaning of eigenvector 1, as the classification based solely on optical emission line width appears to be misleading. Nonetheless, highly accreting NLS1s are still growing in their BH mass.

5 Other Results

My other work spans a variety of AGN related subjects including high redshift quasars, lensed quasars, host galaxies, maser sources, red quasars, properties of broad line region, damped Lyα absorbers, *Chandra* serendipitous source survey, medium-deep fields, blazars, and jets.