Statement of Research Interests:
The Interplay of Baryonic Components in the Universe

Romeel Davé, University of Arizona

1. Overview

Understanding the evolution of baryonic matter in the Universe is a forefront challenge in modern cosmology. While studies of cosmological parameters and dark matter evolution are entering the precision era, there has yet to emerge a clear picture of how baryonic matter transforms from its homogeneous state in the dark ages into today's galaxies, clusters, and intergalactic medium (IGM). The primary focus of my research involves using state-of-the-art cosmological hydrodynamic simulations to investigate the evolution, physical state, and interplay between the various baryonic components in the Universe.

From a cosmological standpoint, baryons divide into four broad components: (i) Diffuse photoionized gas, (ii) The "warm-hot intergalactic medium" (WHIM) that is shock-heated by large-scale structure but unbound, (iii) Hot gas bound in large potential wells, and (iv) Galactic baryons. Simulations suggest that at the present epoch, baryons are roughly equally divided between diffuse, warm-hot, and bound components. While galaxies are historically well-observed through a variety of tracers, the diffuse component is mainly observable via H I Lyman alpha (Lyα) forest absorption, and hot bound gas is primarily detectable through its X-ray emission. In between these regimes lies the "warm-hot" phase that is even more challenging to detect. Understanding the relationship between these mass components is critical to developing a self-consistent picture for the evolution of baryons over a Hubble time.

My research spans all four baryonic phases, with the overall approach being to conduct detailed comparisons of hydrodynamic simulations with latest observations in order to understand the physics and evolution of these phases within a cosmologically self-consistent framework. Simulations provide complementary information to analytic and semi-analytic models, as they can be used to study asymmetric non-equilibrium processes outside of virialized halos in addition to the bound systems themselves. The simulations I have used are mostly SPH-based, beginning with the world's first parallel TreeSPH code (Davé, Dubinski & Hernquist 1997) that I used for my thesis and for most publications until recently. Thanks to algorithmic, speed, and input physic improvements, I now mostly use Gadget-2 from V. Springel, and have already made minor improvements to this code. I have also begun working with Enzo (a publicly available parallel cosmological mesh hydro code), and with P. Pinto I am developing a novel hydro technique that will better handle shocks and two-phase media that are the bane of SPH codes. I generally prefer to run simulations on local Beowulf systems, as I have found access and flexibility to be better than when using large shared machines. I have been heavily involved in building three Beowulfs in the last four years, one at Princeton and two at Steward including our recent 98-processor Opteron systems.

2. Diffuse Intergalactic Gas

For my thesis I studied the Lyman alpha forest and associated metal lines at all observable redshifts. In Davé et al (1997) we conducted careful comparisons of Keck/HIRES data to simulations using the first fully automated Voigt profile fitter, AutoVP, which I made public and has now been used for a wide range of studies within and outside of astronomy. Simulations predict a tight density-temperature relation for photoionized diffuse IGM gas that allows accurate ionization conditions to be reconstructed from H I line parameters; in Davé et al (1998) we exploited this fact to determine a metallicity of [C/H]$= -2.5$ for $N_{\rm HI} \sim 10^{14.5}{\rm cm}^{-2}$ absorbers ($\delta \sim 5$) from associated C IV lines in the HIRES spectrum of Q1422+231. Using pixel-based methods calibrated by simulations, we also found a gradient in metallicity vs. density from O VI/C IV ratios. In Davé et al (1999) we extended our simulations to $z = 0$ using Parallel TreeSPH to study the evolution of the Lyα forest from $z = 3 \rightarrow 0$, finding broad agreement with observations from the HST Quasar Absorption Line Key Project. Once HST/STIS data became available that was able to resolve the Lyα forest in the UV, we performed a more detailed comparison and continued to find excellent agreement, enabling us to constrain the IGM temperature and metagalactic H I photoionization rate (Davé & Tripp 2001). Overall these studies showed that at all redshifts, Lyα forest absorbers arise in diffuse, highly photoionized gas residing in non-equilibrium large-scale structure, and that the main evolutionary trend in the Lyα forest can be summarized as an increase in underlying density with time for a given column density absorber.

The frontier of these studies lies in more carefully examining metal line absorption, both as a tracer of the pre-reionization ($z \gtrsim 6$) IGM where H I becomes opaque, and from $z \sim 2 \rightarrow 0$ to study the extend the (lack of) evolution seen in the IGM metal content from $z \sim 5 \rightarrow 2$. Both studies have strong implications for large-scale feedback processes in the dark ages compared with more recent times. Simulations are crucial for quantifying observational biases and relating 1-D absorption line measures to underlying physical properties of the IGM gas.

3. The Warm-Hot Intergalactic Medium

The WHIM contains a third to half of all baryons today, making it a significant, heretofore mostly undetected reservoir of baryons: the so-called "missing baryons". This generic result comes from an ensemble of simulations having a range of resolutions, volumes, algorithms, and input physics (Davé et al. 2001). WHIM baryons mainly arise from Lyα forest gas that has been shock-heated on filaments, but is not bound in halos. Because this gas has low density, it does not violate soft X-ray background constraints, as we showed in Croft et al. (2001), among others.

At present, observations of intervening O VI absorbers offer the most accessible approach to quantifying WHIM gas, and preliminary investigations suggest they do indeed hold a significant reservoir of baryons. I am collaborating with T. Tripp on studying his slowly-accumulating sample of O VI systems, and J. Prochaska is obtaining deep imaging to study the correlations with galaxies, all of which will be compared to simulations. Simulations lend guidance for separating photoionized versus collisionally-ionized (i.e. true WHIM) absorbers, and a detailed comparison can test the warm-hot paradigm. In addition, Gadget-2 runs suggest that large-scale feedback processes that enrich the IGM may also generate unbound warm-hot gas, so these studies may help constrain global feedback models.

While O VI is observable now, a larger variety of tracers are nearly within reach. Unfortunately STIS died, taking with it our 130-orbit program (PI C. Howk) to observe a range of other high-ionization absorption features in O VI systems, thereby providing constraints on their metallicity and physical conditions. O VII is actually the strongest absorption feature through the bulk of the warm-hot regime, but lies in the soft X-rays where observations are more challenging. While isolated detections have been reported, in Chen et al. (2003) we showed that future missions such as Constellation-X will detect a large number of such absorbers associated with WHIM gas. This gas may also be detected in emission, as Fang et al. (2004) showed for the proposed Missing Baryon Explorer. I am a Co-I on the proposed Baryonic Structure Probe (PI K. Sembach), which is an Origins Probe concept to do absorption line tomography and spectral imaging of the low-redshift IGM.

4. Hot Gas in Large Potential Wells

Since the early 90's it has been theorized that clusters of galaxies contain a significant amount of stored feedback energy in their hot gas. Scaling relations of luminosity-temperature or luminosity-mass do not follow expected virial scalings from massive clusters to groups, but rather show lowered luminosities in smaller systems relative to this "selfsimilar" model; this has been interpreted as increased entropy or energy that reduces the central density. This effect becomes quite pronounced in poor groups below 1 keV, suggesting that the cumulative input of non-gravitational energy ("pre-heating") is comparable to the binding energy of these systems. Thus poor groups represent a unique opportunity to examine the physics of galactic feedback within the most common of galaxy environments.

Recently, it has become evident that a variety of processes may produce observational signatures that mimic pre-heating. One such process is radiative cooling, which removes low-entropy gas from the X-ray emitting phase preferentially in smaller systems due to shorter cooling times. In Davé, Katz & Weinberg (2002) we found that simulations with cooling and no pre-heating produced scaling relations in qualitative agreement with ROSAT data, and entropy profiles that matched subsequent X-ray data showing no entropy core but rather a gradual increase with radius. Unfortunately, these models also overcooled baryons, forming too many stars compared with optical data. Recently, my student Jon Trump found that overcooling in groups is likely solved by feedback as implemented in Gadget-2, yet such feedback has little effect on scaling relations, so is adding much less than 1 keV per baryon to the intragroup medium. Thus the exact details of the entropy history of groups remains unclear.

Chandra and XMM's increased sensitivity will provide valuable insights into these X-ray faint systems. Some interesting areas that I have been exploring include the origin of fossil groups having a single dominant elliptical and a large number of dwarfs, understanding the metallicity of the intragroup medium in terms of Type Ia and Type II enrichment processes within a dynamically mixing system, determining the contribution of gravitational pre-heating in the WHIM to groups' entropy budget, and studying heating by accretion-driven turbulence. Finally, it will be crucial to understand the role of AGN in the energy budget of the ICM, and to critically test models of AGN that are now being developed for cosmological simulations by V. Springel and others, as AGN can easily provide the required pre-heating but in practice is difficult to couple to intragroup gas.

5. Baryons In and Out of Galaxies

My main current interests revolve around studying the formation and evolution of galaxies within a cosmological context. While it has been a longstanding goal of mine to conduct careful comparisons of galaxies to observations, until recently simulations were so far from reproducing galaxy properties that meaningful comparisons seemed unfeasible. Nevertheless in Davé et al (1999b), we studied Lyman Break Galaxies (LBGs) in simulations, finding that LBGs were generally the most massive systems at $z \sim 3$ and that simulations tended to overproduce their number density. With recent improvements both of input physics and dynamic range afforded by Gadget-2, resulting in a resolution-converged star formation rate in broad agreement with data, I have been motivated to revive my comparison machinery, and the results have been rich with puzzles and insights.

With D. Keres, N. Katz and D. Weinberg, we have been exploring ways in which gas enters into galaxies to form stars, and this seemingly simple problem has yielded a wealth of complexity. A significant (re)discovery is that gas accretes in two modes, a canonical "hot mode" where the gas is shock heated to around the virial temperature and then cools quasi-spherically onto the central object, and an underappreciated "cold mode" where the gas emits its gravitational potential in line emission sometimes well outside the virial radius in filamentary structures feeding the galaxy. Our simulations indicate that cold mode dominates in smaller halos ($M < 10^{11} M_{\odot}$), and consequently at early epochs ($z \gtrsim 2$). Our results appear to be qualitatively independent of numerical issues, as analytic treatments yield similar behaviors.

This efficient cold mode is responsible for the early buildup of massive galaxies and the resulting "downsizing" of the galaxy population since $z \sim 2$ seen in various near-infrared and optical surveys, as I have been exploring in available Gadget-2 runs. It may also be directly observable as Lyα or HeII(1640Å) cooling radiation around high-redshift galaxies, as outlined in Fardal et al. (2001) and now being explored in detail by student Yujin Yang. Nevertheless, major puzzles remain, most notably that star formation does not get sufficiently truncated in massive systems as observed in red sequence galaxies, and that it is difficult to reproduce observed ERO's and sub-mm galaxies (Fardal et al. 2002) at $z \sim 2-3$. The general galaxy population at $z \gtrsim 3$ appears to be nicely reproduced, as is being found by my student Kristian Finlator in a comparison with GOODS data. However, some physical process becomes important around $z \sim 2-3$ that is not currently in simulations. AGN feedback is a likely candidate, but is difficult to model. Obviously, any such solution will require consistency not only with the galaxy population but also other constraints such as Lyα forest linewidths and enrichment, ICM entropy profiles and metallicity gradients, and extragalactic background light. I am particularly interested in working towards such self-consistent models by carefully comparing to a range of available observations across a range of wavelengths.

Galactic feedback is the primary missing ingredient in galaxy formation theory today. Studies of the IGM around galaxies provide direct probes of feedback in action. The latest from K. Adelberger et al. is that the majority of galaxies show coincident Lyα absorption that is consistent with expectations from matter clustering, but that a non-negligible fraction show virtually no absorption, indicating that the H I has been evacuated or has very low ionization fractions. While many groups are focused on the H I data (including our study in Kollmeier et al 2003), metal line absorption may also be telling, as large amounts of C IV are seen close to galaxies indicating that the surrounding IGM can't be too hot. It will also be instructive to try to repeat these experiment at low redshifts, where the galaxies can be explored over more bands, including GALEX where direct comparisons can be made to the rest UV-selected LBGs.

Another recent interest is the study of reionization epoch objects. In Barton et al (2004) we explored using a narrow-band Lyα search to detect the objects responsible for reionization, and although simulations suggest it will be difficult, we nevertheless proposed for and received 64 hours of Gemini time with our custom built $R = 125$ filter in a J-band sky window ($1.122\mu \Longrightarrow z = 8.23$ in Lyα) to do such a search in HDF-N. We didn't get much data due to weather, but are currently building a z=7.7 Lyα filter and hope to reject most contaminants efficiently using the filters together. I am also involved with R. Thompson's group to make predictions for LBGs at $z > 7$ as seen in the NICMOS ultra deep field and in future NIR space surveys.

6. Other Scientific Interests

I am interested in constraining the nature of dark matter from astrophysical observations, and have worked on simulations of self-interacting dark matter (Davé et al. 2001), constraining the mass of warm dark matter from Lyα forest observations (Narayanan et al. 2001), constraining the neutrino mass (Croft, Hu & Davé 2000), and studying intergalactic grey dust (Croft et al. 2000). I am also interested in large-scale structure; we developed Filament Statistics to quantify topology (Davé et al. 1997), measured Omega using the mass-to-light ratio as a function of scale (Bahcall et al. 2000), studied halo occupation distributions (Berlind et al 2003, Zheng et al 2004), and compared with SDSS galaxies in luminosity, color, and environment space (Berlind et al 2004).