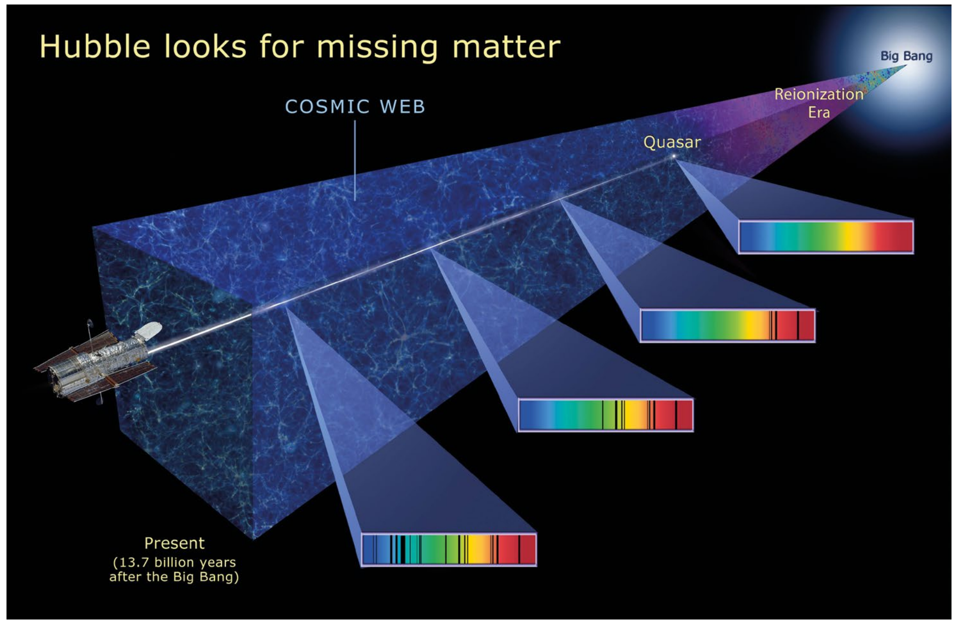
We propose to enhance the legacy of *HST*/ COS by analysing Eulerian hydrodynamic cosmological simulations (EHCS) incorporating physics-based baryon cycle processes

Deciphering the Physics of Galaxy Evolution

Current estimates indicate there are between 200 billion and 2 trillion galaxies in the observable Universe. How these cosmic islands form and evolve in the turbulent, hostile environment of expanding space is important to progress current cosmological models. Using a two-pronged symbiotic approach, **Professor Christopher Churchill**, from New Mexico State University, and his multi-institutional team utilises chemical line spectra received from the *Hubble Space Telescope* (*HST*) and specially adapted, modernised cosmological simulation software to help provide answers.

The creation and evolution of galaxies is an exquisitely balanced process involving multiple cosmological structures. As source repositories of gaseous, baryonic matter (protons, neutrons, etc.), the interstellar medium (ISM, between stars, internal to galaxies), the intergalactic medium (IGM, between galaxies) and circumgalactic medium (CGM, surrounding galaxies, the interface between the ISM and IGM) all provide an equilibrium feedback cycle that dictates the evolution of a galaxy. Due to its composition, the aptly named *baryon cycle* describes this process and its continuous exchange of matter between star systems contained within galaxies and these giant gaseous structures. This closely bound feedback relationship is vitally important to Prof Churchill's collaborative research, as understanding the baryon cycle is fundamental to knowing how galaxies and stars chemically evolve.

Not being a trivial task, obtaining a full understanding of the baryon cycle has been tricky, involving simultaneously comparing chemical absorption line spectra from different epochs in space-time, obtained by Churchill and his team and collected from the *HST* archive of *HST's* 'Cosmic Origins Spectrograph' (COS), and painstakingly modelling them with specialised computer simulations. This arduous task has been complex but is helping to provide the research team with deeper insights to analysing the data and a revolutionary new method of studying galaxy evolution. This novel technique has been critical to research progression, as Prof Churchill highlights that COS conventional analysis of spectra alone relies on too many assumptions to provide a reliable method of describing galaxy evolution.



This shows the *Hubble* looking through a simulation of the cosmic web and collecting the light of a distant quasar. This is how Chris and his team study the simulations, by emulating the real world counterpart of viewing quasars with *Hubble*. Each time the quasar light pierces a gas cloud around a galaxy, it leaves a finger print pattern in the quasar spectrum, as shown in the images of the spectra. They analyse these patterns to understand the baryon cycle.

CIRCUMGALACTIC MEDIUM AND THE BARYON CYCLE

The circumgalactic medium (CGM) has been highlighted as the pivotal regulating component in a galaxies lifecycle. Located in the surrounding regions of galaxies and extending to about 10 times the stellar components of galaxies, the CGM acts as a gaseous interface between the cosmic IGM and galaxies' ISM. The cosmic primordial IGM gas (primarily hydrogen and helium) gravitational falls into the galaxy through the CGM. The metal enriched ISM gas, where stars are born, live out their lives, and die in catastrophic explosions; is blown out into the CGM in galactic scale winds. In the CGM, these two processes collide in what researchers often call "a train wreck". Not only does IGM gas and ISM gas pass through the CGM, it can recycle many times through the CGM during a galaxies lifetime. This flow of material is called the baryon cycle and is important in order *'to establish the physical processes by which baryonic matter responds to and cycles through the dark matter over densities in which galaxies live and evolve'*. For example, it is not understood how the baryon cycle depends on the mass of the dark matter over density in which the galaxy resides. (Dark matter is transparent to the full range of electromagnetic radiation from gamma rays, visible light to infrared and radio, and interacts with baryonic matter only through its gravitational influence). This particular relationship is imperative to understand as it has wider cosmological implications; the cycle of baryons as they pass through dark matter halos is the overarching physical process responsible for what we see when we look out into the universe (i.e., the entire universe of known galaxies is a product of this little-understood process.)

IMPROVED DETECTION IMPROVES THEORY

Historically, analysis of distant galaxies has been achieved by taking absorption spectra. This involves using the received light from a highly luminous target object residing at a cosmic distance behind and slightly offset in the sky from the selected galaxy. Known as quasi-stellar object (QSO), the light that passes through the galactic material is then modified by atomic interactions with various elements and particles. From the received light signal, observed with COS mounted on the *HST*, scientists can deduce many aspects of galaxy composition. Extending this method, galaxies located at different distances, and hence time, can be used to build a complete picture of their evolution. Although this method has served research well, Prof Churchill highlights that, on its own, this technique is not adequately sufficient to produce a complete, modern theory that incorporates an improved understanding of the baryon cycle, and thus galaxy formation and evolution.

The low density gas participating in the baryon cycle of galaxies does not radiate light and must be observed in an absorption spectrum, which provides only a pencil beam probe through the gas. Occasionally a rare view of the spatial distribution of the gas can be seen in silhouette against the host galaxy. This galaxy, imaged by *HST*, shows gas being stripped as it races through the gaseous medium in a much larger cluster of galaxies.

A hydrodynamic simulation showing the cool gas (white) falling into the galaxy and feeding star formation, while hot gas (red) builds up in the CGM around the galaxy. Note the complex intersection of the infalling cool gas and the surrounding hot halo gas. It is this mixing that regulates galaxy formation – and Chris and his team want to understand it! (Max Planck Institute for Astrophysics).

In a ground-breaking, novel advance, Prof Churchill and the research team have taken COS spectra and combined them with specially adapted computer simulations. *'We propose to enhance the legacy of HST/COS by analysing Eulerian hydrodynamic cosmological simulations (EHCS) incorporating physics-based baryon cycle processes.'* By employing this ground-breaking methodology, Prof Churchill and his team aim for a modern revolution in understanding of the CGM and its role in galactic evolution. He emphasises that due to successful computer modelling work in the 1990s, advancement of the Lyα forest/cosmic web paradigm of large-scale structure was brought to fruition. This emphasises the power of the cosmological modelling technique, which when coupled with absorption line spectra has shown to be a winning formula – a formula that he intends to emulate. Part of his research is to run EHCS in a similar fashion to this early pioneering work. Simulations will be carefully designed, implemented, and honed using archived *HST*/COS line spectra. Converting the line spectra from a 1-dimensional point source into a fully developed 3-dimensional model is the ultimate aim of Prof Churchill's work, that will enable galaxy evolution to progress and truly blossom as a branch of astrophysics and cosmology. Additionally, and unique to the research programme, is the ability to isolate stand out activity within the simulations. This will allow researchers to equate signatures in the *HST*/COS spectra with individual gas substructures in the CGM, thus learning about the origin, fate, and role of the gas in governing galaxy evolution. As Prof Churchill highlights, this is critical as this will provide a new view of the baryon cycle, as if we are looking under a microscope for the first time.

FUTURE RESEARCH

Currently, the project has a fully scheduled research timeline running over the next two years. This will be broken down into two distinct phases. Phase one will involve creating and fine-tuning computer simulated galaxy environments and to produce mock spectra that mirror the collected *HST* data. Parameters such as galaxy masses, star formation rates, redshifts, etc., will all be fully integrated into the simulations. Progressing, year two will involve comparing the simulated data with real, COS spectra, which Prof Churchill explains will help to elucidate galaxy dynamics and to provide deeper insights into CGM gas properties and ultimately galaxy evolution itself.

To establish the physical processes by which baryonic matter responds to… dark matter over densities

Q&A

Cycling baryons through dark matter halos is an important aspect of your research. Will your research/findings have an associated benefit in the search for dark matter?

It is true that our work is focused on the regions in the universe where dark matter is at its highest concentrations (what we have called "dark matter over densities"). This is because these are the regions where baryons are gravitationally pulled together to form galaxies deep within the dark matter concentrations (which we call "halos"). However, our work will not provide direct insights into the nature of the dark matter particles themselves

When you study galaxies located at different epochs, is there any evidence to suggest evolutionary processes are different?

In early cosmic epochs, the distance between dark matter halos was smaller, and the galaxies within them tended to interact, collide, and gravitationally merge together. This means, that many small galaxies coalesced into too fewer larger galaxies. These galaxies formed stars at a feverish pace. Today, galaxies are much more isolated, and so they evolve more passively – on their own as it were. Also, the IGM has thinned out as the universe has expanded, so the effects of IGM gas falling into the dark matter halos is diminishing with cosmic time.

Computer simulations are an important aspect of astrophysics and cosmology. With computer power constantly increasing, what are the future possibilities for astrophysics and cosmology?

Regarding galaxy evolution, we wish to exploit the increasing power to provide highly resolved and realistic hydrodynamics in the simulated galaxies. The ISM physics of star formation and death occurs on the scales of fractions of a light year, whereas the evolving cosmological setting in which the galaxies are formed and interact with the IGM is on the scale ranging from 10,000 light years all the way up to 100,000,000,000 light years! It is very challenging to accurately model physics over such a large range of physical sizes. With more power comes more accuracy, comes deeper understanding.

You indicate that your findings will be presented at various special conferences. Where is the best place for the general public to access the information of your research?

I maintain a research page online at http://astronomy.nmsu.edu/cwc/Group/ and in particular, there is a link there "Our Science" in the navigation bar. My personal web page also has some links that are relevant. There are online video talks from the Santa Cruz Workshop on Galaxy Evolution by many researchers in the field:

List of talks: http://hipacc.ucsc.edu/AllTalks.php%3Aid=23.html

My talk: http://hipacc.ucsc.edu/TalkDesc.php%3FTid=393&SerId=23.html

As an eminent scientist at the forefront of research, what advice do you have for any aspiring researchers who want to seek a career in physics and/or astronomy?

Research in physics and/or astrophysics is driven by passion and curiosity. To succeed requires a creative drive not much different than being an entrepreneur. You must develop skills, in this case a strong mathematical background, including computer programming. You must maintain a fresh fertile imagination. You must creatively develop your own ideas on how to ask nature questions that have a chance of being answered with some definitiveness. You must sell your ideas to your peers that your ideas are worth pursuing and that you are a "horse worth backing" to undertake the experiments you design. Then you must be meticulous, detailed, unbiased, and honest in your analysis. You must love to write papers, present talks, and mentor the next generation by training how to do science and lecturing them in the classroom. So, if you are passionate about nature and the human quest to understand it, and you are not afraid of long hours, then jump in with both feet and do not look back. There is nothing like being the only person in the whole human race to be the first to know something previously unknown to any other human (and then to share it with others who share your passions).

Detail

RESEARCH OBJECTIVES

The team's aim with their research is to understand the evolution of galaxies by discovering how the 'baryon cycle' interacts with the circum galactic medium, and to further develop and progress computer cosmological simulations that describe galaxy evolution processes.

FUNDING

National Science Foundation (NSF)

COLLABORATORS

- **Dr Glenn Kacprzak** (Swinburne)
- **Prof Anatoly Klypin** (NMSU)
- **Dr Jacob Vander Vliet** (NASA)
- **Prof Jane Charlton** (Penn State)
- **Dr Sebastian Trujillo-Gomez** (University of Zurich)

BIO

Prof Churchill earned his PhD from the University of California, Santa Cruz, in 1997, and specialises in observational spectroscopic techniques. Prof Churchill heads the Quasar Absorption Line Galaxy Evolution Group, a collaborative effort between New Mexico State University, Swinburne University of Technology, Penn State, and the University of Zurich.

CONTACT

Professor Chris Churchill
Department of Astronomy
New Mexico State University
PO Box 30001, MSC 4500
La Cruces, NM 88001
USA

E: cwc@nmsu.edu
T: +1 (575) 646 1913
W: http://astronomy.nmsu.edu/cwc