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The Baryon Cycle

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Abstract. These are incredibly exciting times for extra-galactic astrophysics; above all for studies of galaxy formation and growth of structure. New observatories and advanced simulations are revolutionising our understanding of the cycling of matter into, through, and out of galaxies. These proceedings provide a short overview of the normal matter in collapsed structures, its chemical make-up and dust content. It includes fresh clues of the cosmic evolution of cold gas; revisit the 20-year old "missing metals problem" and introduce new calculations of the dust content of the Universe up to early times. Together, these results provide an increasingly accurate description of the baryon cycle which plays many crucial roles in transforming the bare pristine Universe left after the Big Bang into the rich and diverse Universe in which we live today.

Key words. baryon density, atomic and molecular gas, cosmic abundances, galaxy chemical evolution, interstellar dust, quasar absorption line spectroscopy

1. Introduction

This work sets to address the relation between baryons forming the gas reservoir which fuels star formation and the cosmic evolution of the star formation rate history. In particular, it looks at which physical processes sustain star formation and explain its global shape with cosmic time. Indeed, a naive view would have the star formation rate increasing as the number of stars increases with cosmic time.

The global redshift evolution of baryons is best quantified by measurements of the mass density, a unitless quantity expressed as:

$$\Omega(z) = \rho(z)/\rho_{\rm crit} = \rho(z)/(3\,H_0^2/8\pi G). \quad (1)$$

where $\rho_{\rm crit}$ is the critical mass density at z=0, G is the gravitational constant and H_0 the Hubble constant.

The total baryonic density of the Universe (see Fig. 1) is well-constrained from Cosmic Microwave Background anisotropies and from light element abundances - measurements based on what happened at two cosmic epochs separated by a factor of a million. We here review the latest measurements of the cosmic evolution of condensed baryons more closely related to the formation of stars with a particular focus on metals and dust.

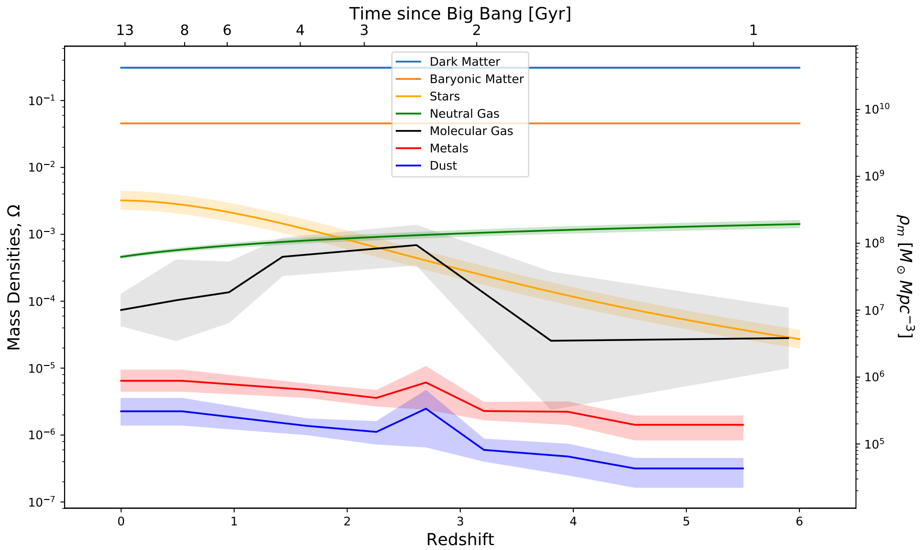

Fig. 1. Cosmological Evolution of Mass Densities. The Dark Energy and Dark Matter (top horizontal blue line) are the dominant components of the Universe, while the total baryonic density of the Universe (horizontal orange line) is estimated from Cosmic Microwave Background anisotropies and from light element abundances is only 10% of the total Universe's matter. But this remaining "normal" matter is still poorly understood. Most baryons are ionised in a phase which is challenging to observe, while we here concentrate on the contribution from various components related to the condense form of baryonic matter: stars (yellow), atomic neutral gas (green), molecular gas (black), metals (red) and dust (blue). *Adapted from Péroux & Howk (2020).*

2. Cosmic Evolution of Baryons

The cosmic evolution of neutral atomic gas, HI, is well-constrained from 21-cm emission observations at low redshift and from quasar absorbers number counts at z>1. The neutral atomic gas mass density decreases by a factor of ~2.5 from z~5.5 to today. Importantly, at z<2.5, the total increase in stellar density exceeds the neutral gas consumption. Observational measurements of the molecular gas mass density are still in their infancy (e.g. Hamanowicz et al. 2022). Current results indicate a rapid decrease at lower redshift, following the shape of the star formation history (Madau & Dickinson 2014). While exciting observational works are coming out, it remains challenging to simulate the colder phase of gas in a cosmological context because of the wide dynamical scales involved (but see e.g. Maio et al. 2022). Fig. 1 indicates that the atomic neutral gas component always dominate over the molecular gas content and that the shape of the molecular gas mass density mirrors the star formation rate history, as the molecular gas is rapidly consumed by making stars.

It is interesting to estimate how baryons cycle through these various phases. The molecular gas depletion timescale, which describes the timescale of conversion of gas into stars, is found to be mostly constant with cosmic time (Péroux & Howk 2020; Tacconi et al. 2020). These results suggest a universal physical process of conversion of molecular gas into stars on global scales. At z<1, the molecular gas consumption time is comparable with the dynamical time, which describes the infall time from the halo virial radius down to the galaxy. For these reasons, the drop in the star formation history is likely driven by a drained gas reservoir.

The observables can further be used to compute the net accretion rate (Péroux & Howk 2020). This quantity describes the rate of accretion (or conversion) from ionised reservoirs given the observed evolution of mass density in condensed matter. This describes both the motion and transformation of gas. This rate decreases continuously with time, dropping below z<2. Interestingly, the baryon mass accretion rate, i.e. the total matter scaled to the cosmic baryon fraction, indicates a 4% efficiency factor. Therefore the conversion of accreted baryons into cold gas is a very ineffecient process. Together, these results indicate that globally the growth of condensed matter (stars and cold gas) in the Universe scales principally with the dark matter accretion rate onto halos. Therefore, the observed decrease of gas accretion is due to the decreased in dark matter halos growth.

Additionally, these observations are consistent with the bathtub/regulator model (Bouché et al. 2010; Lilly et al. 2013; Peng & Maiolino 2014) which describes galaxies as systems in a slowly evolving equilibrium between inflow, outflow and star formation. At early times, gas accumulates and the star formation is essentially limited by the gas reservoir. At later times, galaxies reach a steady state in which star formaiton is regulated by the net accretion rate.

3. Cosmic Evolution of Metals

Metals refer to elements heavier than helium which have been made in stars within galaxies. Two decades ago, Pettini (1999) and other subsequent works noted the paucity of metals compared with expectations in the available data at z ∼ 2. Their expectations were based on some of the earliest estimates of the star formation rate density evolution of the Universe, measurements of metals in neutral gas, and stellar metals from high-redshift galaxies. This missing metals problem spurred many follow-up works about the global distribution of metals in the Universe.

The metallicity of neutral gas is now well-constrained based on statistically significant samples and includes a self-consistent correction for dust-depletion based on multi-element analysis (Péroux & Howk 2020). Results indicate a mild evolution of the HI-weighted metallicity of 1 dex over 10 Gyr. We also note that the scatter of individual points is larger than the global cosmic evolution. Finally, there is a floor below which objects are not found in statistical samples while they could be detect, indicating that pristine gas is exceedingly rare.

The observables are compared with the total metal production by star formation, modulo the fraction of stellar mass immediately returned to gas when massive stars explode. We stress that the expected amount of metals are little dependent on assumptions of the Initial Mass Function (IMF) because the metal production rate is directly related to the mean luminosity density and the yield and massive stars dominate the metal production. The metal mass density also indicates that the neutral gas component dominates over the ionised gas. At z<1, the contribution from metals in groups and clusters is important, but the stars are the dominant contributors to the metal budget. The estimates of the fractional amount of metals in stars rely on assumption of the yields to calculate the total expected amount of metals. These uncertainties are extensively discussed in e.g. Peeples et al. (2014). Surprinsingly, the neutral gas contains all expected metals at z=3 and this remains an open topic of investigation (see e.g. Yates et al. 2021).

We revisit the missing metals problem by calculating the fractional contribution to the total expected amount of metals. Remarkably, at z>2.5, all metals are in the low-ionised gas. At low-redshift, there is a diversity of contributors, most of which are catalogued. At 1<z<2: the likely contributors (including the ionised gas traced by the Lyman-α forest and the hot gas in group & clusters, as well as stars) are not yet catalogued: future UV/X-ray missions (such as LUVOIR, XRISM, Lynx, Athena) are required to close this census. Overall, the expected metal content of the Universe is likely accounted for in contrast with 20 years ago (Pettini 1999).

4. Cosmic Evolution of Dust

The dust is essentially the solid-phase of metals. Indeed, a large fraction of metals is locked into solid-phase dust grains. Dust has a strong influence on observational properties of galaxies but also on formation of the molecules critical to star formation. Hence, the cosmic evolution of dust mass is a fundamental measure of galaxy evolution. We have used the multi-element method for correcting elemental depletion to estimate the amount of the metals locked into dust grains in neutral gas. Properties of dust in neutral gas vs. metallicity is traced by the dust-to-gas ratio, DTG, which is the fraction of the interstellar mass incorporated into grains. We find that the DTG is a strong function of metallicity, it follows the trend of higher metallicity for lower-redshift galaxies. In addition, the new measurements extend at lower metallicity, indicating a change in dust assembly in that regime. Importantly, the fit to the DTG-metallicity relation provides a refined tool for robust dust-based gas mass estimates inferred from millimeter dust-continuum observations (Popping & Péroux 2022). DTG increases by $\sim$1dex over $>$10Gyr in cosmic time, a result of the increase in the mean metallicity. The dust-to-metal ratio, DTM, is the fraction of all the metal mass bound into dust. This quanitity is decreasing with decreasing metallicity. Indeed, the DTM values decrease and have an increased scatter, reflecting the complex dust chemistry at work in low-metallicity environment. Finally, we estimate the cosmic evolution of dust mass density (Péroux & Howk 2020). The dust in neutral gas provides constraints up to z=5.5 and it is in good agreement with other measures where they overlap at z<2. These measurements provide new constraints to the next generations of hydrodynamical simulations incorporating dust physics to understand the galaxy contributors to the global build-up of dust.

5. Conclusions

These conference proceedings focusses on the global quantities of baryons, including metals, dust and stars. It sought to relate the changes in these quantities to one another, as material cycled through the various phases of baryons with cosmic time.

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