Production and Distribution of Matter in the Universe

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Abstract

The generation of matter in the universe occurs in the core of stars through nuclear chain reactions. When a star dies, its collapse produces an immense quantity of energy, throws the generated matter far away at very high speeds, and creates the conditions for the radioactive processes at the foundation of heavy elements. This work summarizes the processes that create and distribute matter in the universe. Furthermore, it dives into the phenomena that give rise to the observability of supernova remnants and other high-energy processes while highlighting the need for space-based measurements of the same. Finally, several observations and discoveries achieved through space missions are presented along with the information they carry about the origin, abundance, and distribution of matter in the universe.

1 Creation of the Matter

Matter is the most pervasive feature of the universe, in particular Baryons, which is the visible matter we interact every day with and which we are made of. Knowing the composition of the universe is fundamental to understanding how abundant certain elements are in the universe. Also, going deep into the details of matter's creation provides us with fundamental insights about how energy can be generated and spent to create specific elements, and how the universe itself was born.

The origin of Baryons is traceable back to the first three minutes of the life of the universe [1], beyond which the first light elements were generated by the aggregation of protons and neutrons, due to fluctuations in a cooling-down cosmos. Hydrogen (H), Helium (He), and small quantities of lithium (Li) were therefore dispersed and started to collapse due to gravity into over-dense gravitational wells. As more and more baryons converge into a single point, they start interacting with each other under motions induced by the ever-growing gravitational pull. Such collapse continues up

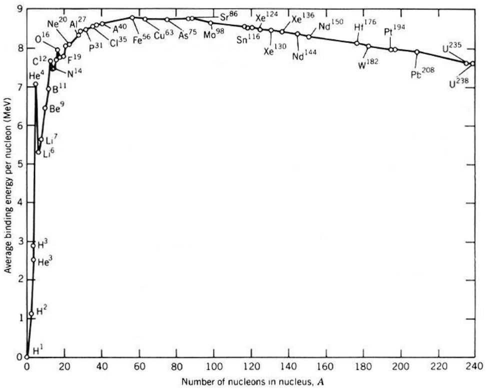

Fig. 1 Binding Energy produced by atomic number

until the point at which those baryons are subject to such intense energetic conditions that they fuse into heavier nuclei, releasing a huge amount of energy. Such nuclear pressure counterbalances gravity and causes the hydrostatic stability of which the stars live out for up to billions of years. For most of their main sequence stable phase, stars burn hydrogen into helium through the proton-proton chain [2], which works as follows: (i) At first, one proton undergoes a $\beta+$ decay as it interacts with another proton, releasing its positive charge as a positron and part of its mass as a neutrino. The outcome of this fusion is deuterium (^2_1H); (ii) In turn, a deuterium and a proton fuse into an unstable helium-3 (^1_2He) atom, releasing energy as γ-rays during the process; (iii) Finally, two unstable helium-3 fuse into a stable helium-4 (^2_2He), expelling two protons during the reaction. This nucleosynthesis process [3] lasts until the hydrogen is completely exhausted inside the core. When this happens, other nuclear chains occur, fusing helium into Carbon (C) and Carbon into Oxygen (O), and the chains continue up to heavier elements as long as the fuel's abundance enables it. However, the efficiency of such energy production decreases as the fusion produces increasingly heavier elements. Figure 1 plots the binding energy with respect to the atomic number of the fused atom [4].

The transition between one atomic number to the next can be interpreted as the energy released in the fusion mechanism from the source to the target element. If the binding energy increases during the transition, then the reaction produces energy, otherwise it absorbs it.

According to the data, the growth of the curve follows a logarithmic growth, with the most energy produced in the proton-proton chain reaction. Interestingly, the trend peaks at the Iron-56 (Fe^{56}) before the binding energy produced starts to become negative. It implies that, after the production of Iron-56, no more energy is emitted by the fusion reaction but instead, energy is required to create heavier elements. That is the reason why the energy produced in Earth's nuclear reactor is generated by fission, that is, by breaking the nuclei instead of fusing them. The fundamental implication behind this physical behavior is that stars are capable of maintaining their internal pressure only while they can fuse elements up until the Iron. And so, the energy furnace that lights up the stars undergoes an intermittent contraction that pauses each time it

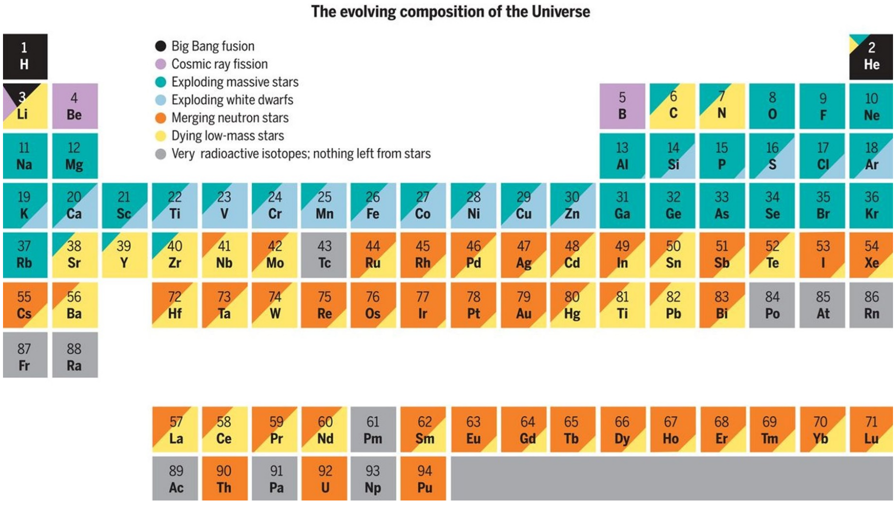

Fig. 2 The Evolving Composition of the Universe

runs out of one fuel, and starts burning the ashes as a new fuel, accreting the density of its core [5]. When lighter elements have moved away from the center and the core is a dense iron mass that exceeds the Chandrasekhar limit, it undergoes a degenerative process in which the material collapses into a neutron star [6].

2 Supernovae Explosion and Remnants

The source of the explosive energy behind supernovae has long been debated by scientists [5]. Such phenomena are capable of lighting up the sky with a luminosity that can match an entire galaxy for a limited amount of time ranging from weeks to months, and are some of the most important events in high-energy astrophysics. The consequence of supernova explosions is the release of a huge amount of matter in a vast surrounding area, throwing off highly energetic particles part of which travel for many light-years, finally reaching us as cosmic rays [7]. These clouds of Supernova Remnants (SNR), due to the nature of such a process, comprehend neutron-rich environments where nuclei enrich their mass by neutron capture, forming heavier elements up to the Rubidium (Rb). Heavier elements undergo different generation processes, some of which are subject to even more extremely neutron-rich conditions. Figure 2 reports a table of the evolving composition of the universe, with each element labeled by its generation process [8].

Furthermore, light elements like Beryllium and Boron, which would be unstable inside the core of a star, are synthesized by Cosmic Ray (CR) spallation, that is to say, the fission of Carbon that collides with interstellar matter [9]. This highlights an interesting property of nuclei, which is to exist in stable and unstable configurations. An atom can exist in many states, still remaining the same element. These states are traceable to the neutral impact that neutrons have on the nucleus. Two elements sharing the same atomic number Z, that is the number of protons, can hold a different number of neutrons N, and so a different atomic mass number Z. These two substances

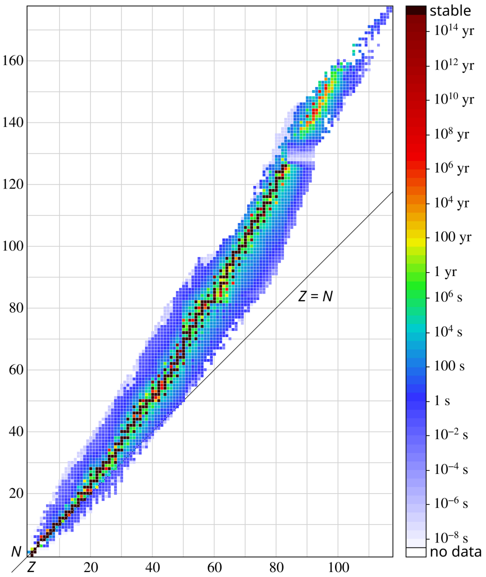

Fig. 3 Stability of Isotopes with respect to Z and N

have similar chemical properties such that they keep sharing the same name, and they are called isotopes. However, some of them are stable whereas others will undergo, after a certain time, a radioactive decay. During this reaction, they expel energy as γ-rays in order to find a more stable configuration. For such a reason, the current process is not only accountable for the diffusion of baryonic matter in the universe but also for the generation of metals heavier than iron and their radioactive isotopes.

To add some detail about elements' stability, Figure 2 plots a set of points with Z and N as coordinates, where each point represents an isotope and the color tones measure their stability in terms of how much the isotope survives before decaying.

Those empirically measured decay times show how the stability is approximately related to a certain proportion between protons and neutrons. The more the exceeding abundance of one with respect to the other, the lower the isotope longevity. Also, by investigating the plot deeper, it is possible to notice some stable isotopes, detached by the main curve, and mostly located at coordinates with even Z and N values. Table 1 summarizes the number of stable elements for even and odd Z and N values [10].

A property that is immediately deducible from Table 1 is that stability is directly related to the parity of the elements. Very few stable elements with an odd number of protons and neutrons have been discovered in nature.

In conclusion, supernova explosions are extremely powerful phenomena that spread matter across the galaxies while SNR extreme neutron-rich conditions are the catalysts for the radioactive processes of unstable nuclei that are accountable for the formation of heavier elements.

Table 1 Stable Isotopes Table

Z	N	Number of Stable Nuclei
Even	Even	157
Even	Odd	53
Odd	Even	50
Odd	Odd	4

Number of stable elements with respect to Z and N parity and disparity

3 Signature of Supernova Explosions and Remnants

Supernovae are very energetic phenomena that manifest through a huge luminosity burst for a short time scale and a continuous emission that fades over time. Also, such an event releases a gas cloud that propagates at high speed and is eventually heated up by a second shock [11]. This high release of thermal energy induced in the interacting interstellar medium and the expelled star material creates a highly energetic and ionized environment, in which electron interactions produce Bremsstrahlung, synchrotron radiation, and emission lines. Those phenomena mostly emit x-ray radiation, even though heating gas is also visible in the infrared band. However, supernova explosions are also responsible for the emission of long Gamma-Ray Bursts (GRB), emissions of photons in the γ-ray spectrum that can be generated for tenths of seconds [12]. Heavy radioactive isotope decay is another important source of γ-ray emission, as already pointed out in 2. As high-energy radiation propagates, it usually interacts with the interstellar medium and experiments with an afterglow which tends to disperse the energy in a broad spectrum of frequencies. This is one of the reasons why supernovae can be observed in a vast interval of wavelengths. Also merging neutron stars can generate short GRBs with a survivability of a few seconds.

Finally, the particles accelerated by all the released kinetic energy of the supernova reach relativistic speeds, and travel as cosmic rays across the universe, “bounced” by the electromagnetic fields in space, interacting with other particles in the interstellar medium before eventually reaching the solar system. [13]

In the end, supernova explosions, which are the main responsible for matter distribution in space, are highly energetic events that, as short and rare as they may be, irradiate the cosmos with all kinds of intense radiation ranging from radio to the γ-ray bands. Even more conveniently, they throw relativistic particle rays that, upon reaching our solar system, provide us with a concrete sample of the chemical composition of the universe. This advantage is even more fundamental when considering that, according to nuclear physics, matter is the same everywhere, and so the conclusion derived from their study can be extended to all places in the universe.

Another important phenomenon that produces heavy elements and GRB, as already mentioned in both this section and 2 is the merging of two neutron stars. This event propagates gravitational waves in the space-time tissue, enriching even more the typology variety of phenomena we can detect in order to better understand the composition of our universe.

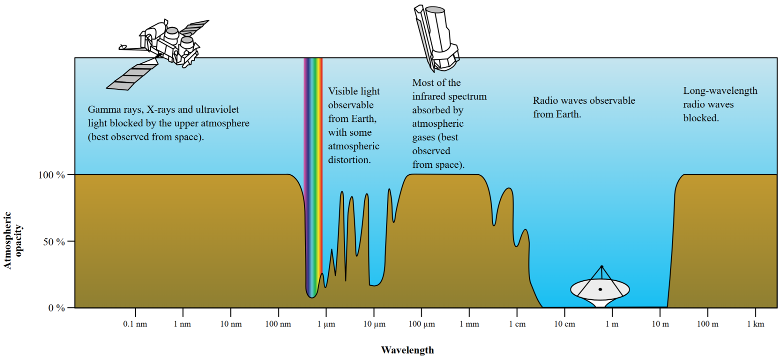

Fig. 4 Atmospheric Opacity at different wavelengths.

4 Space Missions and Detection of Matter

Observing the universe in the electromagnetic spectrum is the more direct approach that humans can follow to study and comprehend very far phenomena in the cosmos. Telescopes are radiation detectors able to capture and measure the intensity of photons and produce data in various digital file formats, among which images. However, the atmosphere represents a critical limitation for electromagnetic measurements made on Earth. This layer of mostly gaseous matter that surrounds the Earth interacts with the electromagnetic waves, creating scattering and attenuating the radiation. In particular, such effects are much stronger in specific portions of the electromagnetic spectrum, cutting off certain ranges of wavelength values. Figure 4 plots the effect of the atmosphere's opacity on electromagnetic waves in different bands [14].

As deducible from such a plot, the only easily measurable bands from the Earth's surface are the optical bands, or visible light, and the radio band.

For this reason, the very first astronomic observations were conducted by scientists by means of the naked eye only. Today, there are many huge electro-optical telescopes hosted in different countries capable of taking pictures with a very high resolution that have been invaluable for many historical astrophysical publications. However, there are still other regions of interest in the lower part of the spectrum that are greatly attenuated such as the UV rays, X-rays, and γ-rays, as there are also in most of the infrared spectrum.

The only way to perform effective measures on this portion of the spectrum is to detect light directly outside of Earth's atmosphere. Hence, space missions play a crucial role in the study of far radiation emitters. From the beginning of the space era, many increasingly sophisticated Space Telescopes were designed to be operative in space, despite the challenging criticalities and the intrinsic risks of such a hostile environment. Figure 4 lists some of the most important deployed space telescopes [15].

The James Webb Space Telescope (JWST) is the most recent infrared space telescope [16]. Product of a collaboration between NASA, ESA, and CSA, it is currently orbiting around the sun at the Lagrangian point 2 (L2) and is equipped with a vast

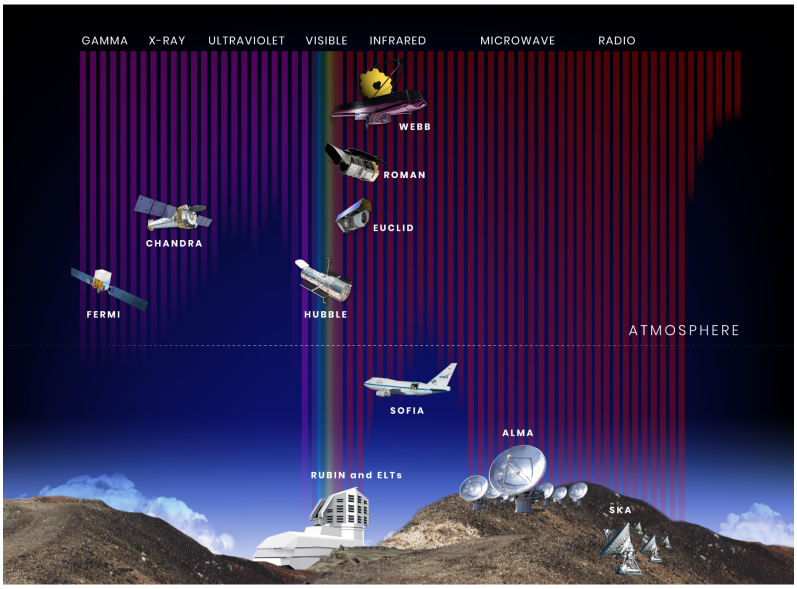

Fig. 5 A representation of some of the most important Space Telescopes.

set of detectors in the near and mid-infrared. Across the year, it helped to characterize many thermal phenomena, which are the main emitters of infrared radiation, from near planetary sources to far high energy emitters, such as nebulae, SNR, and stars.

Regarding X-ray detection, Chandra X-ray Observatory has been a famous NASA mission operative since 1999 [17]. Among some of its most relevant discoveries, there is the SNR Cassiopeia A and many other supernova emissions. In this frame, ESA's mission NewAthena is also planned to be deployed in 2037 as the largest X-ray observatory ever built [18].

A different approach with respect to lower-band signal is required to detect γ-rays. Such devices are composed of many layers of different materials aimed to trigger the generation of particle-antiparticle pairs from γ-rays to measure the intensity in the form of generated heat. One concrete implementation of such a sophisticated mechanism is the FERMI Gamma Rays Telescope launched by NASA in 2008 in LEO orbit, in collaboration with other National Space Agencies including Italy, France, Japan, and Sweden [19]. The telescope carries a Large Area Telescope (LAT) with which it has been able to detect γ-rays bursts and to enrich scientific knowledge about the phenomena that generate γ-rays in SNR.

Finally, gravitational waves are one more crucial phenomenon in the study of supernova explosions and remnants. In particular, for studying phenomena related to neutron stars and black holes. The detection system is founded on the time of travel of light in the void. Discrepancies in such predictable values can be used to detect gravitational fluctuations in the space-time tissue. In this frame, LISA is a planned mission born from a NASA and ESA collaboration and shall be launched by 2030 [20]. It will orbit at the Lagrangian point 1 and will deploy as huge equilateral triangle of communicating detectors with 2.5 million kilometers side in a heliocentric orbit.

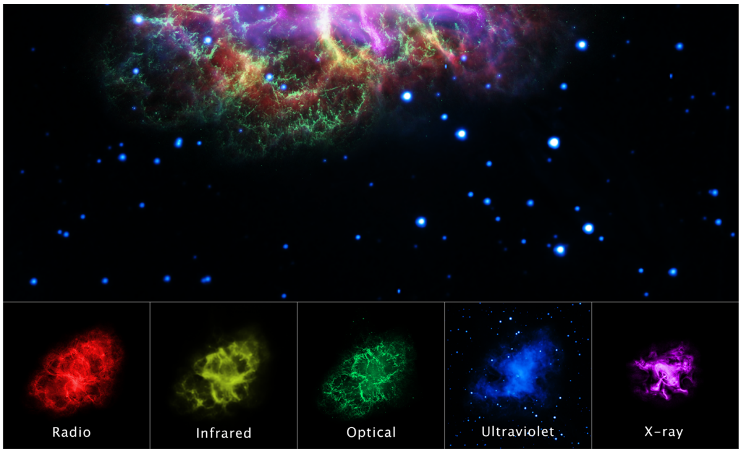

Fig. 6 Multispectral image of Crab's Nebula.

In the end, space missions are the only way for humans to obtain effective information on phenomena manifesting in the electromagnetic bands surrounding the optical range. Space vacuum is also the proper environment to gather observe supercharged particles and to range light speed without interferences from the Earth's atmosphere. As such missions have been operating for years, many discoveries and scientific publications have been released. Eventually, many others will be researched with the launch of the next planned scientific space missions.

5 Observations of Matter's Distribution

The many space missions launched over the years fulfilled the nearby orbits with space telescopes capable of observing different portions of the electromagnetic spectrum with high resolution. This constellation of detectors makes it possible to obtain a complete picture of the most energetic processes in the universe and in our galaxy in particular. Multi-spectral images are space photos obtained by merging multiple photos taken at different wavelengths. As an example, Figure 5 shows the luminosity of Crab's nebula from the radio band up to the x-ray band.

Matter particles undergo many physical interactions involving characteristic energy radiation emissions, such as, for instance, Bremsstrahlung [21], synchrotron [22], and inverse Compton [23]. Furthermore, specific atoms radiate in well-known wavelength bands, meaning that relevant information about the composition of matter can be inferred at very far distances by analyzing the light it emits. In this frame, important discoveries have been made regarding the composition of SNRs.

Another precious source of information about matter's distribution is Cosmic Rays, their compositions having been compared with the one of the Solar System. The outcome of such analysis is evident in Figure 5. There is a relevant lack of Lithium, Beryllium, and Boron in the formation of a stellar system like ours, proving empirically the expected disproportion in the stellar's matter production described in Section 1.

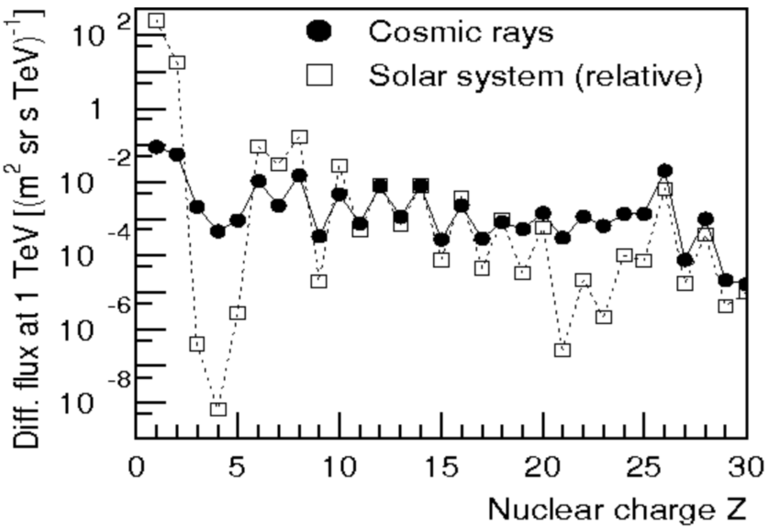

Fig. 7 Abundances of elements in Cosmic Rays with respect to the Solar System distribution.

It is worth noting that matter is a pervasive characteristic of the universe and its processes, and it is the same everywhere. Hence, the invaluable importance of having concrete evidence of matter's distribution.

6 Conclusion

In conclusion, the universe was in principle made of Hydrogen, Helium, and traces of Lithium. The universe's cooling process and the physical interactions between them led to the creation of giant incandescent masses of primordial matter, the stars. Such luminous spheres' core reaches temperatures high enough to trigger the nuclear fusion of such elements, into heavier atoms. As long as this process produces energy rather than requiring it, the star is stable, otherwise its own gravitational pull will make it collapse on itself. Big stars' death releases huge amounts of matter and radiation into Supernovae explosions, some of the most energetic phenomena in the universe. The kinetic energy disperses the newly "forged" heavy elements in a wide area. Furthermore, the explosion produces a neutron-rich environment of supernova remnants, and the star itself collapses into a Neutron Star. The interactions with neutrons create even heavier elements while the released energy travels light-years in the space vacuum in the form of electromagnetic radiation. As it arrives on Earth, most of it will be blocked by the atmosphere, which is the reason why humans deployed many advanced telescopes into space. The data they retrieved helped humans to prove theorized properties of matter generation and distribution in the universe, while also leading to new fascinating discoveries.

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