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**Galactic Archaeology**

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I address the history of our galaxy by a local approach that is in essence the search for fossils. To probe back in time, one can look in our vicinity for the oldest stars. This motivates exploration of the field of galactic archaeology where one effectively digs into the past. Stars that formed long before our Sun are different. They are deprived of most heavy elements. Their orbits and their chemical signatures trace the evolution of the galaxy. We will learn how our galaxy formed by the assembly of diverse fragments of star-forming clouds.

**Cosmology in our back garden**

Some fifty or so dwarfs have been found around the Milky Way. These formed long ago, they are relics from the past. One distinctive feature is that they have a low content of metals. Another is that they contain a lot of dark matter. This tells us that star formation was relatively inefficient at first. This is just as well, for the gas reservoir in the universe is still a dominant component, at least compared to the stars. It is good news that the raw material, gas, remains. Otherwise the bright lights in the Milky Way galaxy would be fading away. Much of the relic gas is the intergalactic medium, and some circulates in the circum-galactic spaces that we recognize as the halos of galaxies.

**The dimness of the night sky**

The most recognizable relics of the past are galaxies that are so faint that they cannot be detected as fuzzy patches of light. Their feeble surface brightness is drowned out by the night sky. Even on the darkest of nights there is the dimmest of glows between the stars, from the accumulation of many distant galaxies in the universe.

The darkness of the night sky is itself one of the paradoxes of cosmology, and has been known for several centuries. Were the universe infinitely large everywhere one looked in the sky there should be stars. Indeed the night sky would be as bright as the sun. Of course this is far from the case. The first discussions of these issues can be traced to the 16th century.

The paradox is named after German amateur astronomer Heinrich Olbers who described the puzzle of the darkness of the night sky in 1823, although it seems to have been defined as early as 1576 by English astronomer Thomas Digges. It was elegantly rephrased by the American writer Edgar Allen Poe in his prose poem Eureka written in 1848:

*Were the succession of stars endless, then the background of the sky would present us a uniform luminosity, like that displayed by the Galaxy – since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the voids which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.*

The explanation of Olbers’ Paradox is either that the universe is finite in space or in time, or indeed both. The Big Bang theory gives a natural resolution of the problem. With modern data, we know that the universe is 13.7 billion years old. If stars have been shining for at most this period, then the night sky is mostly dark. For example galaxies only cover a percent or less of the sky. And most of these are so faint that they can only be seen with large telescopes.

Even a galaxy is mostly empty space, with the stars being widely separated. In the densest of star clusters, the separation between stars may amount to 0.01 light year but the size of a star is typically 0.0000001 light year. In more reasonable units, the separation between stars in a dense star cluster is 1000 astronomical units while the size of a star is 0.01 astronomical units. One astronomical unit is the mean earth-sun distance, one hundred and fifty million kilometers or 93 million miles. The night sky would be full of bright stars as viewed from a planet in a star cluster.

Our sun is in a more typical region; our nearest stellar neighbor Alpha Centauri is 3 light years away. That is why our night sky is so dark, at least in directions out of the Milky Way.

**Ultra-faint dwarfs**

The most pathetically dim galaxies known are the ultra-faint dwarf galaxies. They are so faint and sparse in terms of stars that they are discovered only by counting stars. A typical ultra-faint dwarf has about ten thousand stars. Our Milky Way galaxy has ten billion stars.

There are now some 50 of these ultra-faint dwarf galaxies that have recently been discovered. One can measure the relative motions of many stars in each of these galaxies. The stars have motions of a few kilometers per second. In our Milky Way, the stars circulate around the centre at a speed of some 200 kilometers per second. From the circular motions of the stars in the Milky Way, we determine the total mass of our galaxy. About 90% is in dark matter. For the dwarf galaxies, we find that 99% of the mass is dark. This tells us that the dwarf galaxies must have had a different history from that of a massive galaxy. Star formation was very inefficient in dwarf galaxies.

The theory of galaxy formation predicts that our galaxy should be surrounded by many thousands of dwarf galaxy satellites. We see less than 100. Where are the missing dwarfs? Astronomers have reasoned as follows. The escape velocity for gas to leave a dwarf is relatively low. It does not take much gas heating for the dwarf to lose most of its initial gas reservoir. If 90% is ejected then the remaining gas will eventually form stars, but in greatly reduced numbers compared to what might have been.

Why is the gas ejected from the dwarf galaxies, but not for example from the Milky Way? Here is our best explanation for the cause of the dwarf galaxy deficiency. When the gas cloud cooled and fragmented into stars inside the dwarf dark matter halo, the first massive stars exploded as supernovae after a few million years, long before most of the gas had fragmented. These violent explosions were able to expel most of the gas before it had a chance to form stars. This happened preferentially in dwarfs because of the low escape velocities for gas to leave. All dwarfs everywhere should have been partially destroyed, leaving pale remnants behind, objects that we detect as the ultra-faint dwarfs. A dwarf galaxy is mostly stripped of gas before it was able to form large numbers of stars. Hence most dwarfs are simply invisible, since they contain so few stars. There should be a huge population of invisible dwarfs. But we cannot see them, even with aid of the largest telescopes.

**Field of streams**

As a dwarf galaxy companion circles the Milky Way, it experiences disruptive tidal forces. The tides on the Earth are caused by the proximity of the lunar orbit and the tug of war between lunar and solar gravitational forces. A loose agglomeration of stars suffers far more extreme tidal forces from the Milky Way. Dwarfs too close to our Milky Way are torn apart. This manifests itself as an ever-growing stream of stars spread along the dwarf’s orbit.

To the great surprise of astronomers, the first deep star maps of the entire sky performed by the Sloan Digital Sky Survey in 2005 revealed a field of streams throughout the Northern sky. The Sloan telescope is based at Apache Point in New Mexico and only observed about half of the sky. It mapped millions of galaxies but also mapped millions of stars, many of which are outliers of our own galaxy. Selecting the brightest stars, the red and blue giant stars, the mappers distinguished faint streams of stars: these are the relics of tidally disrupted galaxies. And they also found occasional star piles: these are the ultra-faint dwarf galaxies.

**Nucleosynthetic signatures**

Long dead massive stars leave chemical imprints in low mass stars like our sun. All of the elements, heavier than helium, were synthesized in earlier generations of stars. A massive star burnt its hydrogen into helium. Once the core exhausted hydrogen, its core shrank and heated up until helium ignited. There was brief frenzy of helium burning in to carbon. The intense output from helium results in the outer layers of the star swelling up to form a luminous red giant star.

As the core exhausts helium and further collapses to burn carbon into oxygen, the outer layers of the star are expelled, forming the beautiful objects we see as planetary nebulae, only so named because they resembled planets when first discovered with small telescopes a century and a half ago. What is left in the stellar core is a white dwarf star, an inert mass of carbon and oxygen that is supported not by thermal energy but by the quantum pressure of the electrons. Because of this, no further nuclear reactions occur. Our galaxy is teeming with white dwarfs, testimony that intense episodes of star formation and death occurred billions of years ago.

The above is true for a star like the sun, or for one a few times more massive. For a star of more than ten solar masses, the evolution is more dramatic. It turns into a hot and luminous blue supergiant star, before finally exhausting its nuclear fuel supply. All that is left in the core is iron, the ultimate slag heap of the universe. No further thermonuclear energy can be extracted by fusing iron: it is the most stable of the elements. The star runs out of pressure support, and the iron core collapses into a star thousands of times more compact than a white dwarf, a neutron star. Enormous amounts of energy are released by the collapse, and this powers a supernova explosion of the outer layers of the star.

**Circum-galactic gas**

Were it not for a reservoir of raw material surrounding our galaxy in the form of diffuse hydrogen gas, the bright lights of the Milky Way would have burnt out long ago. The circum-galactic gas supply is a mixture of freshly accreted gas from the intergalactic medium and gas ejected by dying stars.

The halo around our galaxy contains diffuse hot gas at millions of degrees Kelvin and cold hydrogen clouds at hundreds of degrees Kelvin. We observe some of these clouds falling into the Milky Way. They provide fresh fuel for star formation. But they do not provide enough. Our galaxy is forming stars at a rate of a few solar masses per year. The infalling clouds account for only 10 percent of the necessary fuel supply for forming stars. However the mass reservoir of hot gas is much larger.

There is an ingenious way to tap the hot gas supply. Ordinarily it is too diffuse and too hot to cool down. Exploding massive stars in the disk eject huge shells of gas at high velocity. This sweeps up ambient interstellar gas to form a supernova remnant. Many of these shells are swept out into the halo where they mix with the ambient hot gas. In doing so, the cooler shells act like seeds that stimulate the cooling of hotter gas.

This is analogous to how tiny dust particles can seed clouds and rain in the earth’s atmosphere. The net result is that far more comes down than goes up from our galactic disk in this activity, which is known as the galactic fountain. In this way, one can use the reservoir of halo gas that surrounds the Milky Way to maintain the rate at which stars are forming. The heavenly fires continue to burn and the bright lights are not extinguished. The Milky Way still has a brilliant future, for billions of years to come.

**Intracluster gas**

Most of the intergalactic medium has not been consumed in stars. Indeed most of the gaseous matter in the universe is well beyond the confines of galaxies. Clusters and groups of galaxies provide laboratories where one can follow the life cycle of the gas. There is far more diffuse intracluster gas than in stars, about three times as much. The gas is very hot at some tens of millions of degrees Kelvin, and is detected via its diffuse x-ray emission.

One of the most mysterious properties of intracluster gas is that it contains a great deal of iron. Collectively there is more iron in the intracluster medium than in the stars. This is mysterious because it is the dying stars that create and eject the iron in supernova explosions. There is about five times more gas than stars, but half of the gas has probably fallen in and only dilutes the ejected iron from stars. The expected output of iron from dying stars in total is not very different from the mass observed in the intracluster gas, as one might expect in a cluster where the ram pressure due to the galaxy motions is effective at driving out the interstellar gas.

Where does the iron come from? There must have been many more episodes of star death in the past than we would have anticipated from the observed mass in stars. The iron is a fossil from previous generations of massive stars. A massive star exhausts its nuclear fuel supply, produces a core of iron, and explodes.

Ideas differ about the nature of the explosion, but we observe such events. Most of the iron in our galaxy is produced in supernova explosions. Their spectra reveal that as much as a solar mass of iron may be ejected every century into the interstellar medium. Over the age of the Milky Way, about ten billion years, this is more than enough to account for all of the iron in our galaxy.

**Giant radio relics**

Radio astronomers routinely map the debris from violent explosions. These manifest themselves as giant lobes of radio emission, centered on the active nucleus of the host galaxy. They are a testimony to vast explosions in the past, many millions of years ago.

The explosions were triggered by a merger between two massive galaxies. Both galaxies contained a central supermassive black hole and large amounts of gas in addition to their stars. The merging is especially significant for the gas clouds which lose energy and angular momentum as they interact. The mergers thoroughly mix up the orbits of practically all of the stars except those that are far from the new centre, where the two black holes have ended up in a binary pair, orbiting each other. Eventually they are expected to merge together to form a single enormous black hole.

What happens next renders these events visible. The interstellar gas clouds are compressed and fall into the center of the merged galaxies, where they accrete onto and feed the central supermassive black holes. There is a huge explosive release of energy, and it is this that accelerates particles, especially electrons to relativistic energies. These constitute twin highly over-pressured lobes of radio wave emission. Many millions of years later, we see the greatly expanded remnants of the radio lobes as gigantic relic radio sources.

**Fermi bubbles**

The universe glows in gamma rays. A gamma ray telescope was launched into space in 2008 to study cosmic gamma rays, the FERMI gamma ray telescope. It is named after the great Italian-American physicist Enrico Fermi, one of the pioneers of nuclear fission and the atomic bomb. Most of these gamma rays are produced in the explosive release of energy attributed to infall and heating of gas clouds onto supermassive black holes.

Many gamma ray sources are identified with objects called quasars, for quasi-stellar radio sources. These were first discovered as enormously luminous star-like sources, inferred from their spectral redshifts to be at enormous distances. Only a supermassive black hole can generate enough energy as it swallows gas and stars to power these objects. They are known to be at the centers of distant galaxies.

It has been known for some years that there is indeed a supermassive black hole at the centre of our galaxy. It was originally discovered as a radio source called Sagittarius A\*. It is studied by following the orbits of stars very close to the Galactic Centre, and its mass is inferred to be 4 million solar masses. The mass concentration is so extreme that it must be a black hole. Many nearby galaxies are inferred to contain even more massive central black holes. In a few cases, the black holes are active, that is they are undergoing infall of gas that is heated up and results in intense radiation over the entire electromagnetic spectrum. We call these objects active galactic nuclei, and in extreme cases, quasars.

Our own supermassive black hole is quiescent, as are the nuclei of most nearby galaxies. However we believe that supermassive black holes are omnipresent in galactic nuclei, and sporadically light up because of infall of gas clouds or even disruption of a star that ventured too close to the centre of the host galaxy. Because about one percent of nearby galaxies have active nuclei, we infer that the active phase must occupy about one percent of the age of the galaxies, or about a hundred million years. But there could more frequently be lesser explosions.

A few million years ago, there was a dramatic explosion at the centre of our galaxy. The centre of our Milky Way contains the nearest supermassive black hole, and is the only plausible source for the explosion. The explosion is inferred by the presence of huge twin bubbles of plasma being driven out from the Galactic Centre, first discovered in gamma ray maps of the galaxy obtained by the Fermi gamma ray telescope.

We infer that there are strong shock fronts that demarcate the edges of the bubbles. These accelerate particles to produce the energetic particles we call cosmic rays. The cosmic rays smash into ordinary particles of hydrogen and produce gamma rays. It is by viewing the gamma rays that the Fermi bubbles first were detected. Subsequently astronomers searched more carefully in x-ray and radio maps and found faint traces of the bubbles that previously were overlooked. The Fermi bubbles are fossils that testify to the presence of explosions long ago.

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