Diagnostics for mechanical heating in star-forming galaxies

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The atmosphere of the Earth is mainly made up of nitrogen and oxygen and a smaller fraction of many other chemical components. Radiation from our Sun interacts with these species and scatters. On a clear day this interaction results in a blue color. In our everyday life we often experience the presence of clouds. These clouds are composed of water and they have different properties according to the altitude at which they form. In particular, they have densities different from the average density of their surroundings. Clouds come in many shapes and sizes. They interact with the Sun light, blocking part of its spectrum and eventually acting as filters. Thus, when the solar radiation interacts with these clouds, part of it gets absorbed, some it is reflected and the remaining light (radiation) reaches our eyes.

The concept of clouds can be extended to other environments such as galaxies. Galaxies are formed of stars and gas and dust. Matter between the stars occupies most of the volume and is referred to as the *Interstellar Medium*, labeled with the acronym *ISM*. Light from stars interacts with the clouds in the interstellar medium in a similar way as the radiation from our Sun interacts with the clouds in our atmosphere.

The ISM is filled with gas of very low density. The properties of this gas are quite different from that present in the atmosphere of the Earth. For example, in one cm^3, that is the size of e.g. an ice cube, the atmosphere has 10^{19} atoms, while the gas of the ISM is at least 1 millionth of a billion times less dense with a range of densities that spans from 10^{-3} up to 10^6 atoms per cm^3. In terms of thermal properties, the atmosphere of the Earth is characterized by several layers whose temperature varies in between 200 and 300 K (corresponding to $-172\,^{\circ}$C up to $30\,^{\circ}$C). In contrast, the ISM has different phases with a much wider temperature range between 10 and 10^5 K, i.e. from $-263\,^{\circ}$C up to roughly $99700\,^{\circ}$C). In these conditions, atoms and molecules can be excited in more diverse and various ways.

The physical explanation how different colors are produced while radiation interacts with matter relies on quantum physics, in particular on the quantum structure of atoms and molecules. The radiation from the stars interacts with the gas and excites the chemical species inside the ISM. When the ultra-violet (UV) radiation of stars is absorbed by the gas the electrons get excited into higher energy levels. In the molecular case, in addition to electronic excitation, smaller energy differences that are about a hundred times lower are possible. This excitation is associated with the rotation or the vibration of the molecule. While the electronic excitation can result in ultraviolet emission, the rotational transitions produce infrared (IR, wavelengths from 1 μm up to 1 mm) and submillimeter photon emission. The UV radiation has a low penetration depth, just as sunlight interacting with clouds in the atmosphere whereas IR photons can penetrate much larger clouds compared to the UV radiation.

The infrared radiation emitted from clouds can be detected with specially designed telescopes. The most recent and sensitive currently in operation is the Atacama Large Millimeter Array (ALMA) in Chile that can detect very weak signals. Generally IR and submm emission is indicative of star formation in special regions that work as star "factories". For example, in our Galaxy (the Milky Way) around 1 star is born each year. In star forming galaxies, up to 10,000 stars can be born each year. Regions where very luminous stars are born are also regions where they die. The fast rate of stars being born also increases the probability of having stars that are very heavy (up to 1000 times the mass of our Sun). When these stars die, they explode in one of the strongest explosions in the Universe known as *supernovae*. These explosions are 100,000,000,000,000,000,000,000,000 more powerful than the largest nuclear device detonated on Earth. At this scale they cause the gas in the vicinity to get mixed up and heated due to shock waves and turbulence. The heated gas results in various emission that is different from these of quiescent clouds.

Measurement of the temperature of a body is usually performed using specific instruments called thermometers. As we have experienced several times in our everyday life, this functions by having direct contact with the body whose temperature we are interested in. After the thermometer is in contact for a long enough period with that body, it reaches equilibrium as no heat is transferred anymore between the thermometer and the body. A reading of the temperature can be done using the scales available on the thermometer itself, both in the case of analogue or digital apparatus. When we move to the case of extraterrestrial bodies and we wonder about their temperatures it is evident that such direct measurements are not possible; eventually, indirect methods should be adopted in order to determine the temperature and other physical properties of gas between the stars. The most common indirect way adopted makes use of colors and their wavelengths. To appreciate how this works we can use everyday life experiences; for example, we know that molten lava glows red. The red color indicates that the temperature is about 1000 degrees C. A hot metal welding flame glows with a blueish color indicating that the temperature is about 6000 degrees C. This shift in the color is due to a different distribution of the energies of the photons in the electromagnetic spectrum. In the former case, the peak of the distribution of the photons is towards the red (lower energies and longer wavelengths), with a relative deficit in the blue part of the spectrum, whereas it is the opposite in the second case, i.e. the peak of the distribution is towards blueish photons (higher energies and shorter wavelengths) with relatively fewer photons in the red range. When excited through heat or incident radiation, molecules emit radiation in discrete wavelengths, as opposed to the previous examples, where the emitted photons have a broad distribution. Different types of excitation result in different types, wavelengths of emission. The relative intensities of the different emission of the molecules can be used to determine the temperature and the density of the ambient gas. For example, bright emission of HCN at

88 GHz relative to CO 115 GHz indicates temperatures in a star-forming galaxy around 100 K. This is for example a diagnostic for high temperatures (irrespective of what is causing this high temperature). These molecular transitions can be considered not only as a "thermometer" of the ISM, but they can also give hints on particular mechanisms that allow these transitions to occur. We can think of the emission of these molecules as "long distance detectives" for the ISM.

In this thesis, we study the effect of the absorbed turbulent energy, mechanical energy, on the emission of molecules such as HCN and CO mentioned earlier. We have demonstrated that small amount of turbulence are enough to have a big signature on the emission of molecular species. In particular we have studied the importance of the relative intensities of the emission of HCN, HNC, ^{13}CO and their various transitions in tracing the thermal properties of the ISM. The relative intensities among these chemical species were studied under different conditions where the impact of mechanical heating was tabulated. These tables can be used to quantify the amount of mechanical heating in star-forming galaxies for which observations are available. Moreover, information on the mechanical heating can be analyzed, where a model of possible sources for such turbulent environments can be postulated. This is fascinating and challenging because being far from other galaxies we can derive important information with a limited amount of data.