Radio-Chemistry of the Object 3I/ATLAS

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Abstract

The interstellar object 3I/ATLAS has been observed to emit unusual material. Observations to date suggest that this object contains volatile elements, similar to a comet [1, 2]. Calculations show that the object has been exposed to a combination of low temperatures and high levels of radiation for over one Billion years, which could explain the unusual chemistry of the object.

Introduction

In early 2025, an object on a hyperbolic trajectory around the sun was detected and named 3I/ATLAS. Analysis of the object's motion suggests that it has been in interstellar space for at least one Billion years. Traditional observation models suggest that 3I/ATLAS is similar to a comet, and is made of some mixture of water ice, methane ice, ammonia ice, silicates, iron, and nickel. So far, the actual observations differ from the mainstream models.

Radiation exposure in interstellar space is believed to amount to 70 rem per year [3], which is equal to 0.7 joules/kg/year. That is to say, the radiation exposure over 10 million years is 7,000,000 joules/kg, which is enough to vaporize rock. Of course, when this energy is applied over a long period of time, it does not result in vaporization. It results in chemical bond damage and crystal disruption.

Interstellar space is nominally at a temperature of 2.7 Kelvin, and the radiation will not produce a substantial increase in the temperature of the object. Radiation damage will therefore not be annealed by heat. Free radicals, such as atomic Hydrogen, would therefore remain in a semi-stable state as long as the object does not come close to a star.

At the same time, the effect of the radiation on the outer layers of the object would be to sputter material from the surface. For various reasons, Hydrogen would be removed more efficiently than heavier elements.

Physical and Chemical Evolution of Comet Material Under Radiation

When material which is composed of covalently bonded substances (such as water or methane) are exposed to ionizing radiation (such as cosmic rays), the chemical bonds are disrupted, typically creating ions or free radicals. These often consist of single-atom fragments of the original molecule. At low temperatures, these fragments will not always re-combine with another chemical species. Roughly half of the time, these fragments will persist as quasi-stable ions or free radicals.
When metals, such as Nickle-Iron mix, are exposed to radiation, they are not usually modified chemically. Instead, the impact of cosmic rays on the atomic nuclei cause movement of the individual atoms, which results in voids or interstitial nuclei inside of the metallic crystals. Over time, the radiation causes the metal to become amorphous, or porous, or both [4].

Because the temperature of interstellar space is less than the freezing point of Hydrogen (14K), the amount of molecular and atomic Hydrogen builds up during the period when the object is drifting between the stars.

Physical and Chemical Evolution of Irradiated Material Under Higher Temperatures

When an object made of irradiated material travels close to a star, it heats up. When this happens, the most reactive constituents of the mixture start to move around, and they interact with each other. This produces more heat. As a result, interstellar comets begin outgassing earlier than local comets: They have energy stored in the form of irradiated chemicals.

Also, the spectral signature of the outgassing will be different from local comets: The first burst of gas consists of molecular Hydrogen, mixed with dust. This is followed by small particles of ice, lofted by the Hydrogen outflow. When these move into sunlight, you will see a normal-looking coma, even though it forms further than expected from the sun.
In both cases, Hydrogen is difficult to detect using spectrometers.

Nickel Vapor in the Coma of 3I/ATLAS

One of the unusual observations of 3I/ATLAS involves the spectroscopic signature of Nickel. This is strange because Nickel is a metal with a rather high boiling point. It is also strange because Nickel is usually found in space along with Iron, but there have been no Iron spectra reported.

My belief is that we are seeing a chemical called Nickel Carbonyl [5], which has a boiling point of 316K, modestly above room temperature. This chemical is used industrially in Nickel refineries. What seems to be happening is that the original object contained Nickel, probably in the form of small particles. Over time, the radiation caused these particles to become porous. The original object either contained Carbon Monoxide or radiation caused Carbon Monoxide to form in deep space, or both. Once the object started to heat up, the Carbon Monoxide reacted with the Nickel particles to form Nickel Carbonyl, which then sublimated and was carried out into sunlight, where it was detected.

Preliminary Conclusions

3I/ATLAS is quite different from Kuiper Belt Comets, and is also different from Oort Cloud Comets. The big obvious difference is that it has been traveling in cold, interstellar space for a very long time, and has accumulated a lot of radiation damage along the way. (I suspect that, if you got close to the surface of 3I/ATLAS, it would look like an old, dried-up apple.)

Most of the strange observations are caused by extreme radiation chemistry.

References

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NICKEL CARBONYL