

Radio-Chemistry of the Object 3I/ATLAS, v2

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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.

Models indicate that the outer 10-20 meters of the object suggest that a considerable amount of energy may be stored in the form of unstable chemicals, and that these chemicals may release energy when the object's temperature increases during close approach to the sun.

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, possibly as much as ten 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. To provide some intuition about how much energy this is, we point out that 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, while the heat is lost as infra-red radiation.

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 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 Nickel-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.

Penetration of Muon Radiation into a Large Object

Certain authors [5] have pointed out that cosmic rays have a finite penetration into comet-like material. Typical estimates suggest that the outer 10-20 meters of 3I/ATLAS would be disrupted, but that the interior would remain unaffected. This is not correct.

Cosmic radiation consists mostly of protons at MeV energy levels. When they impact matter, some fraction of the energy is converted into muons, which are highly penetrating [6, 7]. If we make the assumption that 1ppm of the initial cosmic ray energy is converted into muons and then deposited into the interior of the object, you get 700 joules/kg/Billion years. This is enough energy to disrupt the molecular structured and any crystal structures.

The present conclusion is that the radiation over several Billion years of travel in the interstellar medium will be enough to cause a large amount of chemical energy to build up in the material.

Energy Storage inside of Nucleus of 3I/ATLAS

As noted above, much of the energy absorbed by an object in interstellar space is re-radiated in the form of infra-red radiation. Some of it, however, is converted into chemical energy, in the form of free radicals and various quasi-stable chemicals. This chemical energy is stored in the bulk of the material, and will remain stable as long as the temperature is low.

Materials like TNT or RDX store over 4,000,000 joules/kg, which is likely to be close to the maximum amount of energy a solid material can store at room temperature. Without doing experiments, it is difficult to be certain about how much energy is going to be stored in an irradiated solid at cryogenic temperatures, but 10% of the maximum seems to be a reasonable lower bound. Call it 400,000 joules/kg.

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 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, cold Hydrogen is difficult to detect using spectrometers.

When the object comes close to a star, two interesting things happen:

First, the increasing temperature causes the reaction rate of various processes in the material to accelerate, which can result in anomalous emission of gas and dust compared to an ordinary comet. Second, these chemical reactions frequently result in increasing heat, which may cause a thermal runaway. In the extreme case, this could result in a detonation.

Nickel Vapor in the Nucleus 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 [8], 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.

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NICKEL CARBONYL