Physicist explains X-rays that shouldn't exist in 'cold' plasma

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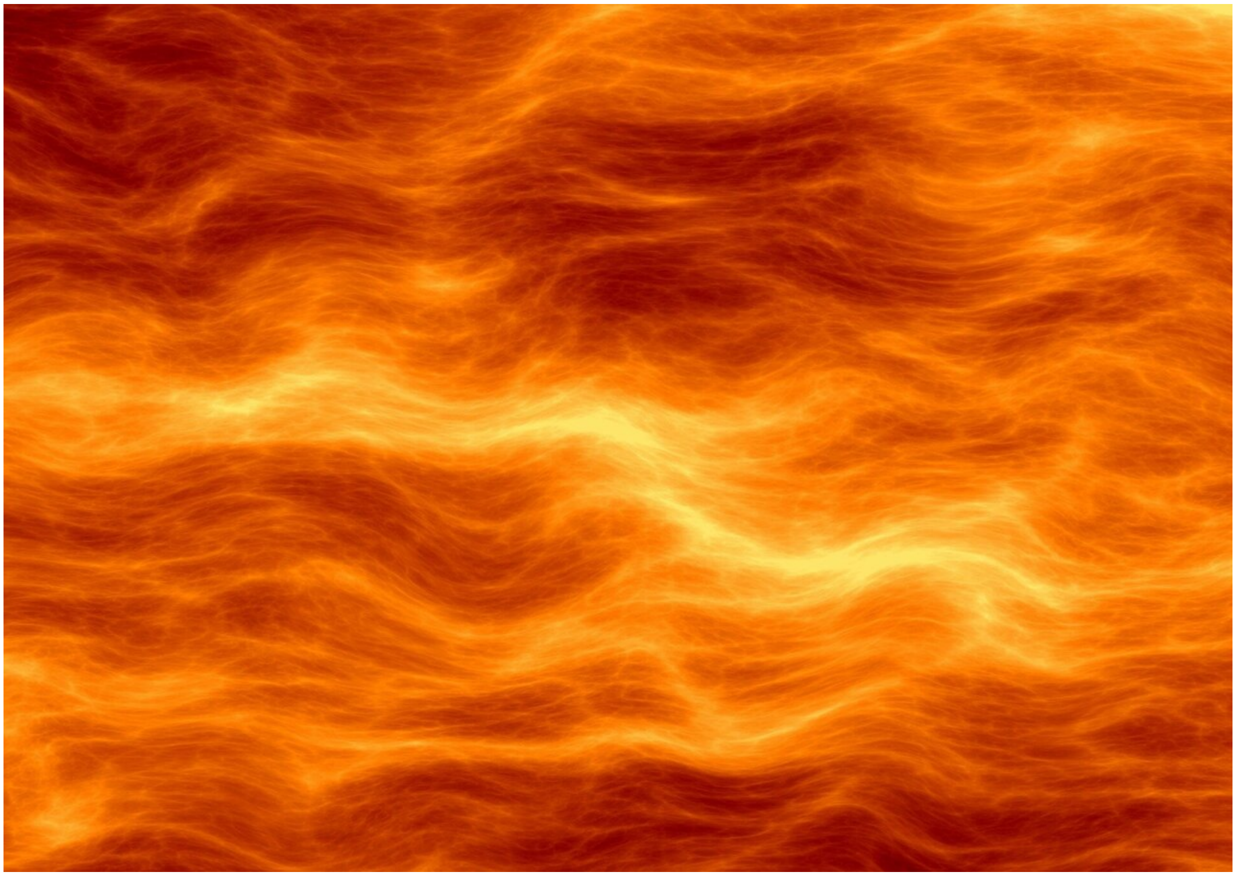

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For about 20 years, Caltech Professor of Applied Physics Paul Bellan and his group have been creating magnetically accelerated jets of plasma, an electrically conducting gas composed of ions and electrons, in a vacuum chamber big enough to hold a person. (Neon signs and lightning are everyday examples of plasma).

In that vacuum chamber, wisps of gas are ionized by several thousand volts. Then 100,000 amps flow through the plasma, producing strong magnetic fields that mold the plasma into a jet traveling about 10 miles per second. High-speed recordings show that the jet transitions through several distinct stages in a few tens of microseconds.

Bellan says the plasma jet looks like an umbrella growing in length. Once the length reaches one or two feet, the jet undergoes an instability that causes it to transform into a rapidly expanding corkscrew. This rapid expansion triggers a different, faster instability that creates ripples.

"The ripples choke the jet's 100-kiloamp electric current, much like putting your thumb over a water hose restricts the flow and creates a pressure gradient that accelerates water," Bellan says. "Choking the jet current creates an electric field strong enough to accelerate electrons to high energy."

Those high-energy electrons were previously identified in the jet experiment by the X-rays they generate, and Bellan says their presence was a surprise. That's because conventional understanding says the jet plasma was too cold for electrons to be accelerated to high energy. Note that "cold" is a relative term: Although this plasma had a temperature of about 20,000 Kelvin (35,500°F)—far hotter than anything humans normally encounter—it is nowhere near the temperature of the sun's corona, which is more than 1 million Kelvin (1.8 million degrees F).

"So, the question is, 'Why are we seeing X-rays?'" he says.

Cold plasmas were thought to be incapable of generating high-energy electrons because they are too "collisional," meaning an electron cannot travel very far before colliding with another particle. It is like a driver trying to drag race through freeway gridlock. The driver might hit the accelerator but would travel only a few feet before smashing into another car. In the case of a cold plasma, an electron would accelerate only about one micron before colliding and slowing down.

The Bellan group's first attempt at explaining this phenomenon was a model suggesting that some fraction of the electrons manages to avoid colliding with other particles during the first micron of travel. According to the theory, that allowed the electrons to accelerate to slightly higher velocity, and once going faster, they could travel just a little bit farther before encountering another particle with which they might collide.

Some fraction of those now-faster electrons would again avoid a collision for a time, allowing them to attain an even higher speed, which would allow them to travel even farther, creating a positive feedback loop that would allow a few lucky electrons to go farther and faster, attaining high speeds and high energies.

But while compelling, the theory was wrong, Bellan says.

"It was realized that this argument has a flaw," he says, "because electrons don't really collide in the sense of hitting something or not hitting something. They are all actually deflecting a little bit all the time. So, there's no such thing as an electron that's colliding or not colliding."

Yet, high-energy electrons do appear in the cold plasma of the jet experiment. To find out why, Bellan developed a computer code that calculated the actions of 5,000 electrons and 5,000 ions continuously deflecting off one another in an electric field. To suss out how a few electrons were managing to reach high energies, he tweaked the parameters and watched how the electrons' behavior changed.

As electrons accelerate in the electric field, they pass near ions but never actually touch them. Occasionally, an electron whizzes so closely past an ion that it transfers energy to an electron attached to the ion and slows down, with the now "excited" ion radiating visible light. Because electrons only occasionally pass so closely, they usually just deflect slightly from the ion without exciting it. This occasional energy leakage occurs in most electrons, which means they never attain high energies.

When Bellan tweaked his simulation, a few high-energy electrons capable of creating X-rays appeared. "The lucky few that never come close enough to an ion to excite it never lose energy," he adds. "These electrons are continuously accelerated in the electric field and ultimately attain sufficient energy to produce the X-rays."

Bellan says that if this behavior occurs in the plasma jet in his Caltech lab, it probably happens in solar flares and astrophysical situations as well. This may also explain why unexpectedly high-energy X-rays are sometimes seen during fusion-energy experiments.

"There's a long history of people seeing things that they thought were useful fusion," he says. "It turns out it was fusion, but it wasn't really useful. It was intense transient electric fields produced by instabilities accelerating a few particles to extremely high energy. This might be explaining what was going on. That's not what people want, but it is probably what happens."

The paper describing the work, "Energetic electron tail production from binary encounters of discrete electrons and ions in a sub-Dreicer electric field," was published in the October 20 issue of *Physics of Plasmas* and was presented on November 3 at the 65th Annual Meeting of the American Physical Society Division of Plasma Physics in Denver, Colorado.

More information: Paul M. Bellan, Energetic electron tail production from binary encounters of discrete electrons and ions in a sub-Dreicer electric field, *Physics of Plasmas* (2023). DOI: 10.1063/5.0167004

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