Space weather is difficult to predict—with only an hour to prevent disasters on Earth

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The interaction of solar winds and the Earth's atmosphere produces the northern lights that dance across the night sky. Credit: Benjamin Suter/Unsplash, CC BY-SA

Recent developments at the forefront of astronomy allow us to observe that planets orbiting other stars have weather. Indeed, we have known that other planets in our own solar system have weather, in many cases more extreme than our own.

Our lives are affected by short-term atmospheric variations of weather on Earth, and we fear that longer-term climate change will also have a large impact. The recently coined term "space weather" refers to effects that arise in space but affect Earth and regions around it. More subtle than meteorological weather, space weather usually acts on technological systems, and has potential impacts that range from communication disruption to power grid failures.

An ability to predict space weather is an essential tool in providing warnings so that mitigation can be attempted, and to hopefully, in extreme cases, forestall a disaster.

The history of weather forecasting

We are now used to large-scale meteorological forecasts that are quite accurate for about a two-week timescale.

Scientific weather forecasting originated about a century ago, with the term "front" being associated with the First World War. Meteorological prediction is based on a good knowledge of underlying theory, codified into massive computer programs running on the most advanced computers, with huge amounts of input data.

Important aspects of weather, like moisture content, can be measured by satellites that monitor continuously. Other measurements are also be readily taken, for example, by the nearly 2,000 weather balloons launched each day. Exploring the limits in weather forecasting gave rise to chaos theory, sometimes called the "butterfly effect." The buildup of error brings about the two-week practical limit.

In contrast, the prediction of space weather is only truly reliable about one hour in advance!

Solar effects

Most space weather originates from the sun. Its outermost atmosphere blows into space at supersonic speeds, although at such low density that interplanetary space is more rarified than what is considered a vacuum in our laboratories. Unlike winds on Earth, this solar wind carries along a magnetic field. This is much smaller than Earth's own field that we can detect with a compass at the surface, and vastly smaller than that near a fridge magnet, but it can interact with Earth, with an important role in space weather.

The very thin solar wind, with a very weak magnetic field, can nevertheless affect Earth in part because it interacts with a large magnetic bubble around Earth, called the magnetosphere, over a very large area, at least a hundred times as big as the surface of our planet. Much like a breeze that can barely move a thread can move a huge sailing ship when caught on the large sails, the effect of solar wind, through its direct pressure (like on a sail) or through its magnetic field interacting with Earth's, can be enormous.

As the origin point, the sun itself is a seething mass of hot gas and magnetic fields, and their interaction is complex, sometimes even explosive. Magnetic fields are concentrated near sunspots, and produce electromagnetic phenomena like solar flares (the name says it all) and coronal mass ejections. Much as with tornadoes on Earth, we know generally when conditions are favorable for these localized explosions, but precise prediction is difficult.

Even once an event is detected, if a large mass of fast, hot and dense gas is shot in our direction (and such a "cloud" in turn is difficult to detect, coming at us against the glare of the sun), there is a further complicating factor in predicting its danger.

Detecting magnetic fields

Unlike the detectable, sometimes even visible, water content in the atmosphere that is so important in meteorology, the magnetic field of gas ejected from the sun, including in hot and denser clouds from explosions, is almost impossible to detect from afar. The effect of an interplanetary cloud is greatly enhanced if the direction of its magnetic field is opposite to Earth's own field where it hits the barrier of Earth's magnetosphere. In that case, a process known as "reconnection" allows much of the cloud's energy to be transferred to the region near Earth, and accumulate largely on the night side, despite the cloud hitting on the side facing the sun.

By secondary processes, usually involving further reconnection, this energy produces space weather effects. Earth's radiation belts can be greatly energized, endangering astronauts and even satellites. These processes can also produce bright auroras, whose beauty hides danger since they in turn produce magnetic fields. A generator effect takes place when dancing auroras make magnetic fields vary, but unlike in the generators that produce much of our electricity, the electric fields from auroras are uncontrolled.

The electric fields from auroras are small, and undetectable to human senses. However, over a very large region they can build up to apply a considerable voltage. It's this effect that poses a hazard to our largest infrastructure, such as electric grids. To predict when this might happen, we would need to measure from afar the size and direction of magnetic field in an incoming space cloud. However, that invisible field is stealthy and hard to detect until it is nearly upon us.

Satellite monitors

By the gravitational laws of orbits, a satellite continuously monitoring magnetic fields by direct measurement must sit about a million miles (1.6 million kilometers) from Earth, between us and the sun a hundred times further away. A magnetic cloud causing minor space weather effects usually takes about three days to come from the sun to Earth. A truly dangerous cloud, from a bigger solar explosion, may take as little as a day. Since our monitoring satellites are relatively close to Earth, we only know about the crucial magnetic field direction at most one hour in advance of impact. This is not much time to prepare vulnerable infrastructure, like power and communication networks and satellites, to best survive.

Since the fleets of satellites needed to give better warning are not even on the drawing boards, we must rely on luck in the face of space weather. It may be a small comfort that the coming solar maximum—when the surface of the sun is at its most active during a cycle and is expected to peak in 2025—is predicted to be mild.

It may be Mark Twain who said "it is hard to make predictions, especially about the future," but it is certainly true in the case of space weather.

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