The magnetic field of a molecular cloud revealed

A combination of standard and new observational techniques has been used to detect the magnetic field of a molecular cloud — a region of the interstellar medium that collapses during star formation. The results suggest that such clouds are primed for collapse earlier than was typically assumed.

The problem

An essential component of the interstellar medium is its magnetic field. During the formation of a star, this field dissipates and regions known as molecular clouds collapse under gravity, leading to the nuclear-fusion reactions that power stars. The strength of the interstellar magnetic field is extremely difficult to measure[1]. The only direct way to measure it is through the Zeeman effect — the splitting of a spectral line into several components in the presence of a magnetic field. However, the main components of a star-forming gas are molecules, most of which either produce a weak, and therefore hard-to-detect, Zeeman effect or are prone to have complex chemistries that make them difficult to locate[1].

The solution

In 2003, the spectra of molecular clouds were found to contain a feature called atomic-hydrogen narrow self-absorption (HINSA)[2], which was thought to be produced when hydrogen atoms are cooled through collisions with hydrogen molecules. Since its detection, the Zeeman effect for HINSA has been deemed a promising measure of the magnetic field in molecular clouds. HINSA has a line strength (a measure of how prominent a spectral feature is) that is 5–10 times higher than those of molecular tracers such as hydroxide, cyanide and dicarbon monosulfide. Moreover, HINSA responds strongly to a magnetic field and, unlike most molecular tracers, is robust to astrochemical variations in the molecular cloud — including both the envelope and the dense core. Observing the HINSA Zeeman effect with sufficient resolution requires a large telescope that can detect radiowaves of decimetre wavelength and that is well-calibrated for measuring the polarization of those waves.

Ever since its commissioning phase, we have been calibrating the polarization measurements of the Five-hundred-meter Aperture Spherical radio Telescope (FAST)[3] in China. After a year of normal operation, we achieved a clear detection of the Zeeman effect in L1544 (Fig. 1), a dense core in the Taurus molecular cloud that has yet to form stars. The L1544 spectrum has a high signal-to-noise ratio of the L1544 spectrum, so it could be decomposed into multiple atomic-hydrogen emission lines and one HINSA feature, from which the magnetic-field strength could be derived. We found that the magnetic field had an ordered structure throughout a region called the cold neutral medium, as well as throughout the molecular envelope and dense core, in terms of both its orientation and its magnitude. This picture was supported by further analysis incorporating existing measurements of the Zeeman effect based on the absorption and hydroxyl emission of a quasar (an active supermassive black hole). The relatively low (4 microgauss) and constant magnetic-field strength throughout L1544 implies that the transition from magnetic subcriticality (able to support the cloud against gravity) to supercriticality (the cloud collapses) occurs in the envelope, and not in the core, as previously thought.

Future directions

How the interstellar magnetic field dissipates to enable the collapse of the molecular cloud remains an unsolved problem in star-formation research[4]. The main proposed solution has long been a process known as ambipolar diffusion — the decoupling of neutral particles from ionized gas — in cloud cores. The ordered magnetic field revealed by the HINSA Zeeman effect suggests that dissipation occurs during the formation of the molecular envelope, possibly through a mechanism other than ambipolar diffusion.

Given that decimetre-wavelength radiowaves need to be detected, even an aperture as large as the 300-metre aperture of the FAST results in only a 3-arcminute beam — the area of the sky in which waves can be detected. As a consequence, even the cloud cores closest to Earth are barely resolved. However, because HINSA can be produced when cosmic rays split apart hydrogen molecules and these atoms are rarely depleted by sticking to dust grains, its full potential to analyse the magnetic-field structures in dense cores has yet to be realized.

To extend this work, we are taking a systematic survey of the HINSA Zeeman effect in star-forming clouds, potentially increasing the number of magnetic-field measurements for such clouds. We are also exploring whether data can be combined from single telescopes and telescope arrays to resolve the magnetic-field structures in dense cores.

Di Li and **Tao-Chung Ching** are at the National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China.

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EXPERT OPINION

"This is an extremely important observation that uses a new tool to show that the transition from magnetically subcritical to supercritical interstellar cloud support occurs in the molecular envelope rather than in the core, contrary to a major theory of magnetically controlled star formation. There remains considerable uncertainty regarding the part that magnetic fields play in the star formation process, so the addition of this tool and result is valuable."

Richard Crutcher is at the University of Illinois, Urbana, USA.

FIGURE

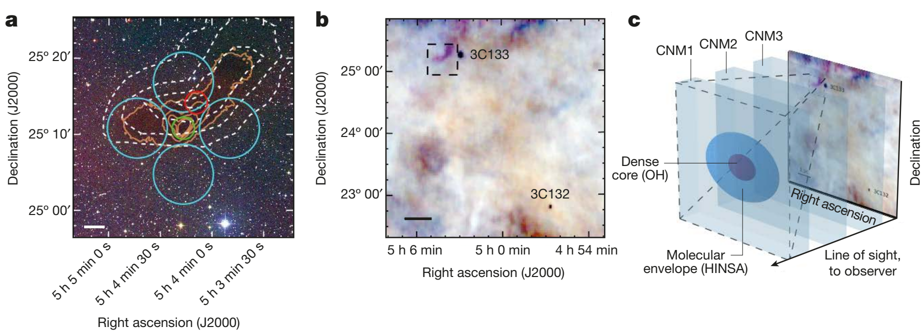

Figure 1 | The dark cloud L1544. a, A composite image of L1544 overlaid with contours indicating regions that produce spectral features for HINSA (white) and molecular hydrogen (orange). The circles mark locations of Zeeman-effect observations for the FAST (red), Arecibo (green) and Green Bank Telescope (orange), respectively. **b**, A composite image of atomic hydrogen surrounding L1544. The box shows the location of L1544 and the positions of two quasars, 3C132 and 3C133. **c**, A schematic view of cold neutral medium (CNM) regions and the molecular envelope and dense core of L1544. Scale bars, 1 parsec. Ching, T.-C. *et al.*/*Nature* (CC BY 4.0).

BEHIND THE PAPER

Only four years after the ground-breaking discovery of atomic hydrogen in space in 1951, the detection of atomic-hydrogen self-absorption was reported[5]. The title of that paper conveyed both exploration and uncertainty. In the 1990s, a major upgrade to the Arecibo Telescope in Puerto Rico allowed it to produce highly sensitive spectroscopic observations, leading to the detection of HINSA. I started my graduate years in the mid-1990s at Cornell University in Ithaca, New York, which operated Arecibo. Our attempt to detect the HINSA Zeeman effect using Arecibo was unsuccessful, possibly because of the complex blockage of the telescope's overhanging structures. Nevertheless, the science–engineering wonder of Arecibo always left me in awe, and I owe the telescope my early career and later opportunity to work on the FAST[3]. The focusing of radiowaves on a cable-driven cabin in the FAST resulted in clean optics, which enabled our current work.

D.L.

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FROM THE EDITOR

This work stood out because the authors use a new observational technique to measure the strength of the magnetic field in the cold atomic-hydrogen gas surrounding a star-forming molecular cloud core. From that and previous measurements, they conclude that the magnetic field no longer supports the cloud against gravity farther away from the star-forming core than was previously thought — a finding that informs our understanding of star formation.

Leslie Sage, Senior Editor, *Nature*