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Decades-Long Changes of the Interstellar Wind Through Our Solar System

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The journey of the Sun through the dynamically active local interstellar medium creates an evolving heliosphere environment. This motion drives a wind of interstellar material through the heliosphere that has been measured with Earth-orbiting and interplanetary spacecraft for 40 years. Recent results obtained by NASA's Interstellar Boundary Explorer mission during 2009–2010 suggest that neutral interstellar atoms flow into the solar system from a different direction than found previously. These prior measurements represent data collected from Ulysses and other spacecraft during 1992–2002 and a variety of older measurements acquired during 1972–1978. Consideration of all data types and their published results and uncertainties, over the three epochs of observations, indicates that the trend for the interstellar flow ecliptic longitude to increase linearly with time is statistically significant.

Neutral interstellar gas, originating in the Local Interstellar Cloud (LIC) now surrounding the heliosphere (*1*), creates a wind through the heliosphere that traces the LIC velocity and temperature. During the 40 years over which spacecraft have measured the direction of the neutral interstellar wind, the relative Sun-LIC velocity of 23.2 ±0.3 km s^{-1} (*2*) has carried the Sun over 1% of the distance to the LIC edge (*1*) and has carried a column of interstellar dust and neutral gas past Earth that is 200 astronomical units (AU) long (*2*–*4*). Turbulence in interstellar plasma is found over 12 orders of magnitude in spatial scale (*5*, *6*), so that comparisons between the wind measurements obtained from NASA's Interstellar Boundary Explorer (IBEX) and older data can be used to look for temporal variations in the neutral interstellar wind.

Most recently, the IBEX mission (*7*) has measured neutral atoms in the interstellar wind. The interstellar neutral helium (He^o) wind velocity and temperature are obtained from in situ IBEX data collected during 2009–2011 (*2*–*4*) and from the in situ data collected during the 1990s with the Ulysses spacecraft (*8*). The He wind velocity vector obtained from IBEX versus Ulysses data differs by 3.6° ± 0.7° in direction and 3.1 ± 0.5 km s^{-1} in speed; the main directional difference occurs in the ecliptic longitude of the He^o flow direction (table S1). The difference between the IBEX and Ulysses measurements motivates a search for past temporal variations in the interstellar wind direction.

He is the most useful diagnostic of the interstellar wind because it is abundant and is only minimally affected by processes in the outer heliosheath, including effects of the interstellar magnetic field. Interstellar He^o atoms follow ballistic trajectories from the heliopause to the inner heliosphere. Neutral He is depleted by ionization on the upwind side; on the downwind side it is concentrated by gravity into a focusing cone that follows the Sun as it moves through the LIC (supplementary text S1)

We used three types of historical data on the ecliptic longitude of the interstellar wind direction (Fig. 1 and table S1) to evaluate possible temporal variations: (i) direct in situ sampling of neutral interstellar He atoms (*2*, *8*); (ii) resonant scattering of solar 584 Å emission off of the spatial interstellar He^o distribution along the observation line of sight (*9*–*14*); and (iii) sampling the spatial He^o, Ne^o, and O^o distributions inside of 1 AU through their production of pickup ions (*15*–*17*). Direct neutral atom imaging provides the full kinematic interstellar flow distribution in the inner heliosphere, taking advantage of the Sun's gravitational deflection of the flow to deduce the flow vector at infinity. Resonant scattering and pickup ion observations sense the spatial distribution of the interstellar gas in the inner heliosphere, as shaped by the combination of gravitational deflection and ionization loss, largely symmetric about the inflow axis. The 584 Å observations provide the line-of-sight integral for atoms with radial velocities sufficiently small to be influenced by variations in the solar 584 Å emission line (supplementary text S2). Through pickup of newly ionized He atoms by the interplanetary magnetic field (IMF) and convection with the solar wind, the latter method maps the radial distribution inside the observer location into a pickup ion energy spectrum, affected by temporal variations of the solar wind and IMF (*18*). Less useful measurements that are not used here include the resonant fluorescence of solar H^o Lyα (912 Å) emission off of interstellar H^o, which is strongly sensitive to the phase of the solar cycle and the deflection of H^o in the outer heliosheath; and the interstellar wind direction obtained from interstellar dust grains that couple to the time-variable solar wind magnetic field by the Lorentz force and, for smaller grains, respond to radiation pressure (supplementary text S3).

In order to compare the recent flow longitude found from the IBEX measurements with other values, we used the allowed longitude range that is independent of the fits to velocity and temperature, 76° to 82° [fig. 1 in (*2*)]. The extremes of this longitude range imply temperatures that are inconsistent with both IBEX and Ulysses cloud temperatures. We further narrowed the temperature range by using the LIC temperature obtained from measurements of interstellar gas toward the nearby star Sirius (supplementary text S4), in combination with the temperature-longitude relation as deduced from IBEX observations (*2*), to impose limits of $\lambda = 80.0°\ (+2.0°, -1.0°)$ on the IBEX flow longitude.

Ulysses obtained in situ flow measurements over three time intervals during the years 1990–2002, and outside the ecliptic plane and thus farther from the Sun than IBEX and with reduced gravitational deflection of the He^o trajectories. We used the He^o flow directions for each time interval (table S1) rather than the best He^o flow direction derived from 12 years of combined data, 75.4° ± 0.5° (*8*).

The first measurements of the interstellar He^o wind direction occurred in the 1970s and detected resonantly scattered solar 584 Å emission fluorescence from interstellar He^o using data from Space Test Program 72-1 (STP 72-1) (*9*), Mariner 10 (*10*, *11*), SOLRAD 11B (*12*), and Prognoz 6 (*13*) (table S1 and supplementary text S2). Looking at the 1970s subset of data and summing uncertainties quadratically, we find that the average ecliptic longitude of the interstellar wind, 73.4° ± 1.3°, differs by ~0.9σ from the interstellar wind longitude obtained from 584 Å measurements by the Extreme Ultraviolet Explorer (EUVE, table S1).

An obvious question is whether differences in modeling of the He^o trajectories could explain the low values for the 1970s longitudes. The only early analysis that used a complete thermal ("hot") model for the interaction of the interstellar gas with the heliosphere was applied to the SOLRAD 11B data (*12*). This analysis yielded a flow longitude of 73.6° ± 3°, which differs from the IBEX

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value by 2σ if the Sirius temperature constraints (supplementary text S4) are applied.

The symmetry axis of the gravitational focusing cone was derived from data collected by the Advanced Composition Explorer (ACE) during five crossings during 1998–2002 (*15*) and two crossings during 2006–2009 (*17*). During 2007–2009, MESSENGER made four passages through the gravitational focusing cone inside of 0.6 AU (*17*).

Pronounced temporal variations are found for the focusing cone geometry in He, Ne, and O pickup ion data acquired by the Solar Terrestrial Relations Observatory [STEREO (*16*)] during four orbits in 2007–2010. These ions trace abundant interstellar species that are partially neutral in the LIC (*1*). STEREO detected a broad upwind "crescent" in the He, Ne, and O pickup ions, where the observed rates maximize in the upwind direction and fall off symmetrically toward the sidewind directions because of ionization. STEREO also measured He and Ne in the focusing cone. Because of variations in the focusing cone count rates, STEREO data were analyzed using two methods. Analogous to the ACE analysis (*15*), the data were summed over all orbits in the first method and the sum was fit with a Gaussian to find the symmetry axis. The second method corrected for solar wind and IMF variations, mostly due to corotating interacting regions, by taking these effects into account when folding pickup spectra through the instrument response and before averaging over all four orbits. Compared with the simpler method 1, the focusing cone axis was found to be at a larger longitude by +2.4 °, with part of the shift due to the response function of the instrument (method 2 directions are listed in table S1). This difference suggests that systematic uncertainties in the average focusing cone axis obtained from the 1997–2002 ACE data (table S1) may have been underestimated.

These data (table S1) on the interstellar He flow direction, which represent three measurement techniques, 19 independent measurements, and data collected with 11 spacecraft over three epochs starting in 1972, show an increase of the flow longitude with time. Although the trend is weak for each data group alone, it appears independently in the He^o 584 Å fluorescence data, in situ measurements, and pickup ion measurements of the focusing cone symmetry. Comparing results from the three different types of observations collected during the 1990s yields similar He flow directions (*18*). ACE measurements at different times (*15*, *17*) yield a statistically significant increase of the flow longitude of 2.6° ± 1.6° over a 10-year period. The significance of this trend depends on the measurement uncertainties of individual data sets, which are taken from the original publications (table S1 and supplementary text S2).

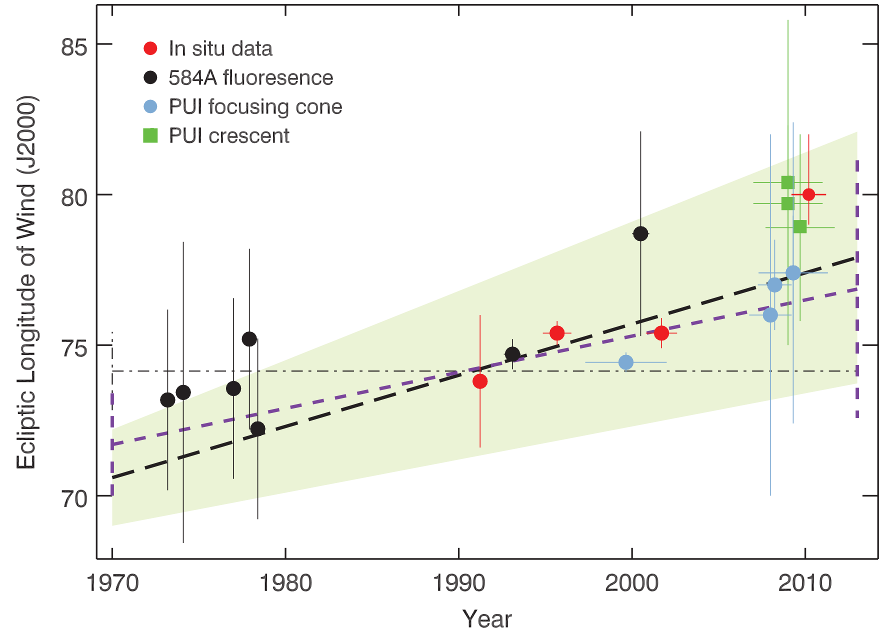

Fig. 1. Historical variations of the ecliptic longitude of the interstellar wind direction. PUI, pickup ions. Measurements of the interstellar wind longitude are plotted against the time span over which the data were acquired. The historical data (table S1) are based on observations of the He^o 584 Å backscattered emission (black), in situ He^o measurements (red), and pickup ion data showing the focusing cone (gray-blue) and upwind crescent (light green). All data are plotted with dots, except for the crescent data, which are plotted with squares. The black long-dashed line shows a statistically likely fit to a simple model in which the flow longitude increases linearly with time, calculated by considering the longitude uncertainties and window of time of the observations; the green shading shows the uncertainties on this fit (supplementary text S5). The purple short-dashed line shows a statistical fit to a model with linearly increasing flow longitudes, where only the longitude uncertainties are included; the two vertical purple short-dashed lines show the uncertainties at each end of the time interval under consideration (supplementary text S5). The black horizontal dash-dotted line shows the fit resulting from the statistically unlikely assumption that the flow longitude has been constant over time and uncertainties on that fit (vertical black dash-dotted line). For clarity, some of the STEREO and Prognoz 6 data points are plotted using small shifts in the year of observation. The temporal interval over which some data were acquired is smaller than the plotted symbols.

Consideration of all data types over the three epochs of observations indicates a statistically significant trend for the interstellar flow ecliptic longitude to increase with time, provided that the uncertainties are realistic. For normally distributed uncertainties, the best-fitting linear model of the flow longitude is $\lambda(\text{deg}) = 70.6\ (\pm 1.6) + 0.17\ (\pm 0.06) \times t_{1970}$, where t_{1970} is the elapsed time in years since 1970. This hypothesis is statistically highly likely, with a reduced χ^2 of 0.97 and a P value of 0.49 (where a P value of > 0.05 is likely; see the explanation in supplementary text S5). The alternate hypothesis that the flow direction has remained constant over the past 40 years is rejected with a P value of 0.031 and a reduced χ^2 of 1.71. It is possible that some of the uncertainties on the pre-2000 data were underestimated; thus we repeated the statistical analysis by scaling the uncertainties for all 20th-century data by a factor s. When the pre-2000 uncertainties were scaled according to $s > 1.77$, the hypothesis of a constant (invariant) flow longitude is more likely. When the pre-2000 uncertainties were scaled according to $0.47 < s < 1.77$, the hypothesis of a linearly increasing longitude is more likely. Thus, for the choice between the hypotheses that the longitude of the interstellar wind has either stayed constant over the past 40 years or increased linearly over the past 40 years, the latter choice is statistically more likely. The statistical model with normally distributed uncertainties suggests a variation of the He flow direction over the past 40 years of 6.8° ± 2.4°. The data and the statistical tests show that a single constant value of the flow longitude is statistically highly unlikely, with a linear increase being far more probable. However, these tests are not adequate to determine whether this temporal variation is actually either linear or some more nonlinear function (supplementary text S5).

The direction of the interstellar magnetic field shaping the heliosphere has been determined from the Ribbon of energetic neutral atoms detected by IBEX (*7*). The Ribbon forms where sightlines are perpendicular to the interstellar magnetic field draping over the heliosphere, and the field direction is given by the center of the Ribbon arc located at λ,β = 221°, 39°. If the LIC gas and magnetic field direction are decoupled over spatial scales of 200 AU and less, so that the field direction has remained unchanged over the past 40 years, a ~6.8° shift of the He^o flow direction between the 1970s and 2011 has increased the angle between the gas velocity and magnetic field direction from 41.5° to the present 48.3°.

Temporal variations in the He flow direction have implications for the outer heliosphere and for the LIC. The 200-AU length of the column of interstellar gas passing over the Sun during 40 years is comparable to the collisional scale length in the LIC [≲300 AU (*6*)] and to the thickness of the heliosphere bow wave (*19*). The ~6.8° azimuthal shift corresponds to 24 AU at 200 AU. If this shift in the flow angle is due to nonthermal turbulent motions in an interstellar eddy, the angular scale of this eddy, $\delta\lambda$, for bulk flow velocity V_{bulk} (*2*) and turbulent velocity b_{turb} (supplementary text S4) would be $\delta\lambda \sim 2\ b_{\mathrm{turb}}/V_{\mathrm{bulk}} \sim 8°$, which is comparable to the observed shift.

There is no obvious bias in the data that would explain the longitude trend shown in Fig. 1, although possibly some uncertainties were underestimated. The variation in the interstellar wind longitude indicated by these historical data may be evidence for variations in the galactic environment of the solar system.

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Supplementary Materials

www.sciencemag.org/cgi/content/full/341/6150/1080/DC1
Supplementary Text S1 to S5
Figs. S1 to S3
Tables S1 and S2
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Radio Jets Clearing the Way Through a Galaxy: Watching Feedback in Action

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The energy released by an active galactic nucleus (AGN) has a strong impact on the surrounding interstellar medium (ISM). This feedback is considered to be the regulating factor for the growth of the central massive black hole and for the rate of star formation in a galaxy. We have located, using very-long-baseline interferometry, the fast outflow of neutral hydrogen in the young, restarted radio-loud AGN 4C12.50. The outflow is located 100 parsec from the nucleus where the radio jet interacts with the ISM, as well as around the associated radio lobe. These observations show that the radio plasma drives the outflow and removes gas from the central regions and that jet-driven outflows can play a relevant role in feedback mechanisms.

The important role for galaxy evolution of energetic feedback effects due to activity in the galaxy's nucleus has been put, in recent years, on more solid grounds thanks to the discovery of massive gas outflows in a growing number of galaxies with an active galactic nucleus (AGN). Many questions are still open, however—in particular, regarding the nature of the driving mechanism of these outflows [e.g., (*1*, *2*)]. Answering these questions is important because it has implications for how ubiquitous the AGN-related feedback is, whether it is connected to specific phases in the life of an AGN, and whether it is a recurrent phenomenon. One of the best ways to answer these questions is to identify the location of the outflowing gas and to image its distribution and kinematics. So far, this has not been achieved given the parsec-scale spatial resolution required to resolve the gas outflow.

The kinetic push of radio jets is often considered a possible mechanism for driving a gas outflow because of the high efficiency with which jets can transfer energy to the interstellar medium (ISM). However, their narrow opening angle is often used as an argument that their impact cannot be very high because a narrow jet would affect only a small part of the ISM. Yet, recent numerical simulations (*3*, *4*) have shown that a radio jet, especially when the radio source is in an initial phase and surrounded by a porous, clumpy medium, may be able to efficiently clear up the gas in which it is enshrouded. This is because a large cocoon of disturbed and outflowing gas is created around the jet by the interaction of the radio plasma, thus affecting a much larger region of the galaxy.

We have imaged, on parsec scales, the distribution and kinematics of the fast outflowing component of the neutral hydrogen in 4C12.50, one of the best-known ultraluminous infrared galaxies (ULIRGs) that hosts a young—recently restarted—radio-loud AGN. Galaxies like 4C12.50 are particularly relevant because they are considered to be the link between ULIRGs and AGNs (*5*); hence, they represent a particularly interesting phase in the evolution of a galaxy. The intriguing and fascinating characteristic of 4C12.50 is the presence of fast outflows not only of ionized gas (*6*, *7*), but also of cold gas—in particular, atomic hydrogen (HI) and molecular gas (CO). An HI outflow of ~1000 km s^{-1} has been previously detected (*8*) that was later found (*9*) to have a markedly similar counterpart of molecular gas [CO(1-0) and (3-2)] (Fig. 1). These gaseous components have been interpreted as being part of the same fast outflow of cold gas.

In 4C12.50, all the possible mechanisms that could drive fast gas outflows are potentially present (*10*): starburst wind (connected to the relatively young stellar population), radiative AGN wind-driven outflows (connected to the bright optical AGN with high-ionization gas), and a powerful radio source. The presence of a particularly strong interaction between the radio jet and the ISM has been suggested by the presence of a hot spot with a very high fractional polarization (60%) at the end of the radio jet (*11*). Although the starburst wind has been ruled out as driving the outflow (*10*), the other possibilities remain. To locate the outflowing gas, we have performed observations with milliarcsecond (mas) angular resolution, using very-long-baseline interferometry (VLBI).

The observations were performed using a global VLBI network, including the Very Long Baseline Array (VLBA), one antenna of the Very Large

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