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No meridional plasma flow in the heliosheath transition region

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Over a two-year period, Voyager 1 observed a gradual slowing-down of radial plasma flow in the heliosheath to near-zero velocity[1] after April 2010 at a distance of 113.5 astronomical units from the Sun (1 astronomical unit equals 1.5×10^8 kilometres). Voyager 1 was then about 20 astronomical units beyond the shock that terminates the free expansion of the solar wind and was immersed in the heated non-thermal plasma region called the heliosheath. The expectation from contemporary simulations[2,3] was that the heliosheath plasma would be deflected from radial flow to meridional flow (in solar heliospheric coordinates), which at Voyager 1 would lie mainly on the (locally spherical) surface called the heliopause. This surface is supposed to separate the heliosheath plasma, which is of solar origin, from the interstellar plasma, which is of local Galactic origin. In 2011, the Voyager project began occasional temporary re-orientations of the spacecraft (totalling about 10–25 hours every 2 months) to re-align the Low-Energy Charged Particle instrument on board Voyager 1 so that it could measure meridional flow. Here we report that, contrary to expectations, these observations yielded a meridional flow velocity of $+3 \pm 11\ \mathrm{km\,s^{-1}}$, that is, one consistent with zero within statistical uncertainties.

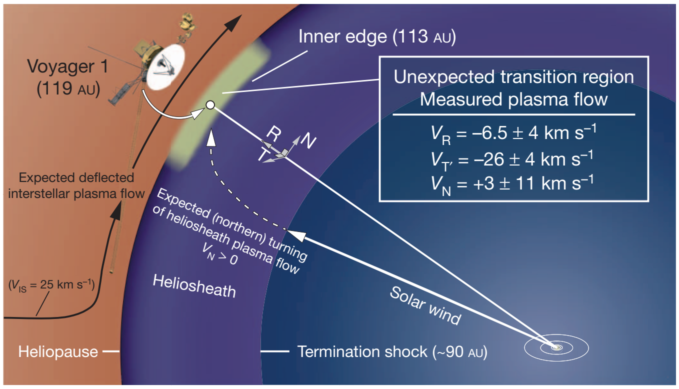

Figure 1 | Heliospheric plasma boundaries and flow regions relative to the location of Voyager 1. The solar wind flows initially radially outwards from the Sun, and in the outer heliosheath its expected meridional deflection becomes parallel to the heliopause. The interstellar flow is from the left in the image; it should be deflected around the heliosheath in the region beyond Voyager 1. Voyager 1 is shown in its own meridional plane (in solar heliospheric coordinates) within the unexpected transition region that it first encountered at a helioradius of ~113 AU (ref. 1; unit vectors of the heliospheric RTN system are indicated). It had been expected that heliosheath plasma flow near the heliopause would have a near-zero radial component and that its meridional component V_N would be a significant fraction of $25\ \mathrm{km\,s^{-1}}$, to be consistent with the distant speed of the local interstellar plasma and its deflection around the heliosheath. However, from the data taken during five rolls of Voyager 1, we have determined that $\langle V_R \rangle = -14 \pm 14\ \mathrm{km\,s^{-1}}$ and $\langle V_N \rangle = +3 \pm 11\ \mathrm{km\,s^{-1}}$. We conclude that the roll data taken at Voyager 1 are statistically consistent with $V_N = 0$. Figure adapted from an image online on the Voyager website at the Jet Propulsion Laboratory (http://voyager.jpl.nasa.gov/news/new_region.html).

The discovery by Voyager 1 of the zero radial velocity[1] of heliosheath plasma flow beyond ~113.5 astronomical units (AU) in a previously unsuspected transition region (Fig. 1) led to the suggestion that the initially radial flow in the heliosheath was already being deflected polewards (towards meridional flow), as predicted by typical magnetohydrodynamic models[2,3]. The suggested meridional flow could not be measured by the Low-Energy Charged Particle instrument in the usual orientation of its scanning plane on board Voyager 1, so starting in March 2011 the spacecraft was commanded to rotate about its Earth-pointing axis for about one day every second month to enable the instrument to measure flow speeds in the meridional or R–N plane. (In the RTN coordinate system, R is the radius vector from the Sun, T is in the direction of solar rotation and N completes a right-handed system.) Measurements from five such rolls performed during 2011/066–2012/030 have been analysed so far (date notation is

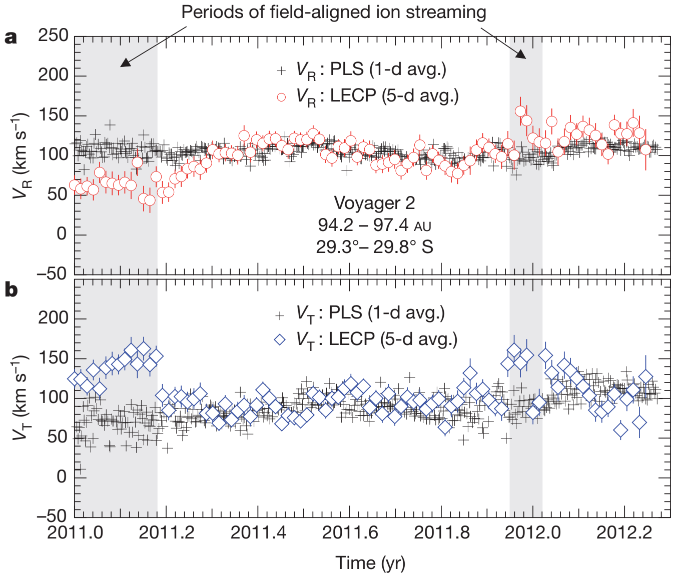

Figure 2 | Comparison of radial and azimuthal components of heliosheath plasma flow velocity at Voyager 2. **a**, Crosses, daily averaged values of V_R measured by the plasma instrument (PLS) during 2011/001–2012/035. Circles, 5-d-averaged determinations of V_R using the Fourier fit procedure on 28–43-keV ion angular data from the Low-Energy Charged Particle instrument (LECP). Vertical error bars are Poisson statistical uncertainties ($\pm 1\sigma$) about the mean. During the period shown, Voyager 2 moved from helioradius 94.2 AU to helioradius 97.4 AU and from heliolongitude 29.3° S to heliolongitude 29.8° S. **b**, Crosses, daily-averaged values of V_T measured by the PLS. Diamonds, 5-d-averaged determinations of $V_{T'}$ using the Fourier fit procedure on ion angular data. Vertical error bars are Poisson statistical uncertainties (2σ) about the mean. There is generally good agreement between the measured solar wind components and those determined from fits to the low-energy ion angular measurements. The two shaded periods show where angular data on ions in several energy channels of the LECP allow us to identify relatively large non-convective anisotropies consistent with $+T$-directed streaming along the average azimuthal orientation of the magnetic field in the heliosheath.

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year/day of year). We report here the absence of a statistically significant persistent N component of flow, with a cumulative average velocity over the five roll periods of $\langle V_N \rangle = +3 \pm 11\,\mathrm{km\,s^{-1}}$. Longer-term averages of the R and T components of flow during 2011/066–2012/030 in the usual instrument orientation yielded a sunward radial velocity of $V_R = -7 \pm 4\,\mathrm{km\,s^{-1}}$ and a persistent negative azimuthal velocity of $V_{T'} = -26 \pm 4\,\mathrm{km\,s^{-1}}$.

We test the null hypothesis for convective flow in the N direction, that is, that the meridional component (V_N) of any convective plasma flow within the transition region is statistically consistent with zero. Thus, we make the simplest assumption of convective flow in our most sensitive energy channel (ions with energies of 53–85 keV) and compute the velocity implied by the angular distribution of ion intensities. If that velocity is consistent with zero within our estimated errors, then we conclude that there is no measureable V_N.

The Low-Energy Charged Particle telescope samples the anisotropy of the energetic ion intensity in seven positions spaced by 45° in its scan plane; one sector was intentionally blocked. The counting rates $C(\phi_n)$ in the seven usable sector positions ($n = 1, 2, \ldots, 7$) overdetermine the first five coefficients in the Fourier expansion

$$C(\phi) = C_0(1 + A_1\cos(\phi) + B_1\sin(\phi) + A_2\cos(2\phi) + B_2\sin(2\phi)) \quad (1)$$

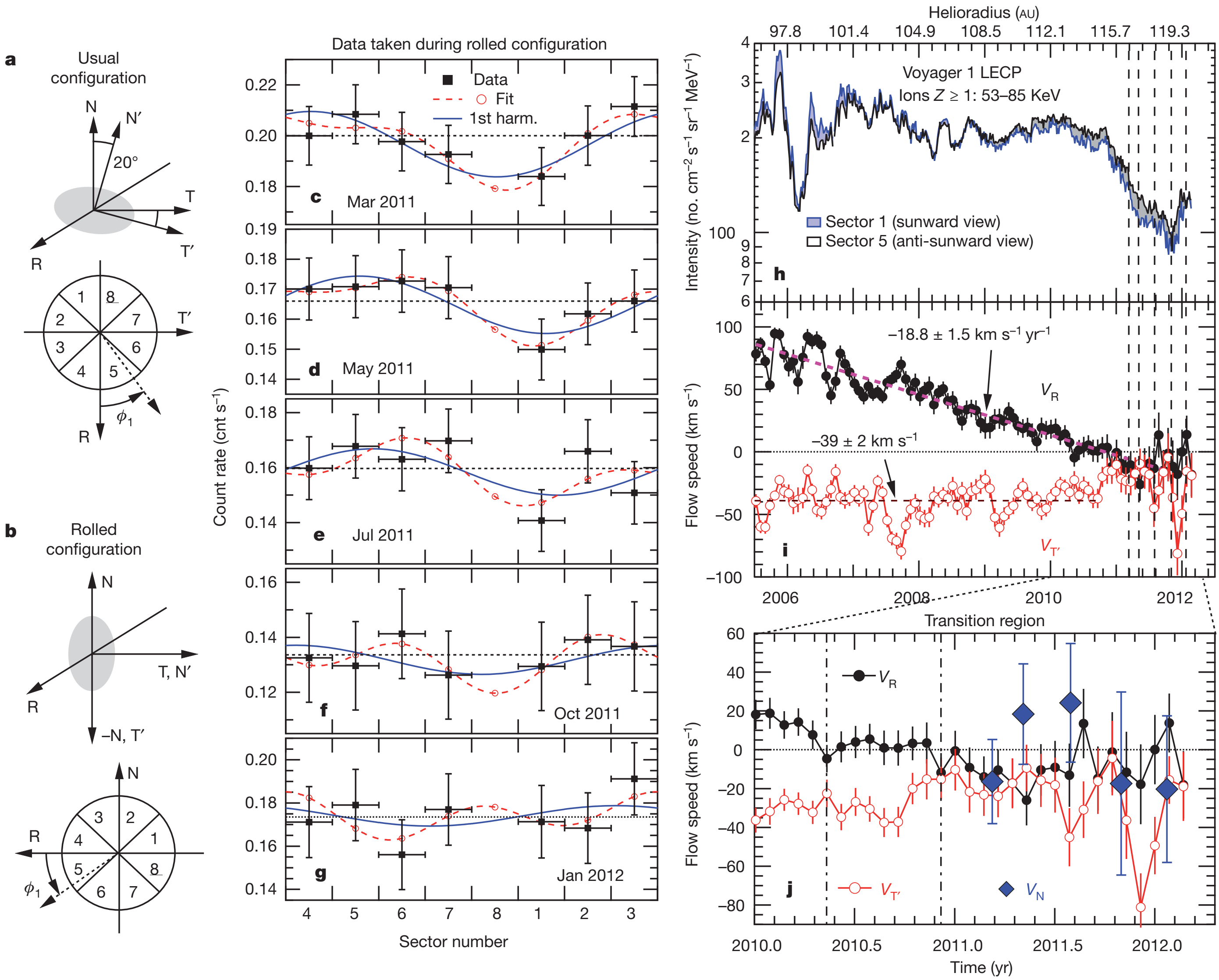

Figure 3 | Roll measurements and derived components of heliosheath flow velocity. a, Top, orientation of heliospheric (RTN) and instrument-associated (RT′N) axes at the location of Voyager 1 in the usual spacecraft configuration. The LECP scans in the R–T′ plane (shaded grey). The N′–T′ plane is rotated about the R axis by 20° relative to the N–T plane. Bottom, view along the +N′ axis showing sector positions in the R–T′ plane (sector 8 is blocked) and the first-order anisotropy angle ϕ_1. **b**, Top, orientation of axes in rolled spacecraft configuration. Bottom, view along the +T = +N′ axis showing sector positions in the R–N plane. **c**–**g**, Count rates versus sector in rolled configuration for five roll periods. Solid symbols are roll-averaged count rates of 53–85-keV ions, predominantly protons, based on independent composition measurements. Vertical error bars are Poisson statistical uncertainties ($\pm 1\sigma$) about the mean. Horizontal bars indicate sector angular width. The red curve is a least-squares fit to data of the function in equation (1). The blue curve is the first-harmonic component of the fit. **h**, Intensity of 53–85-keV protons. The blue and black traces are respectively the intensities in sectors 1 and 5 of particles arriving from the sunward (sector 1) and anti-sunward (sector 5) directions in the usual spacecraft configuration. The helioradius of Voyager 1 is given along the top axis. The dashed vertical lines indicate the roll periods in panels **c**–**g**. **i**, 26-d-averaged plasma flow velocity components V_R and $V_{T'}$ (roll periods not included). Vertical error bars are Poisson statistical uncertainties (2σ) about the mean. For comparison, the average value of the solar wind speed is $\sim 400\,\mathrm{km\,s^{-1}}$. **j**, Expanded view of panel **i** including the five roll determinations of V_N (diamonds). Vertical error bars are Poisson statistical uncertainties (2σ) about the mean. The first dot–dash vertical line shows the onset, at ~2010/133, of a 208-d (2.05-AU) stretch of zero V_R; the second dot–dash vertical line, at ~2010/341, marks the end of the steady zero-V_R flow and the transition to variable and often negative-V_R flow. Anisotropies in the usual configuration after ~2010/341 show non-convective features in sectors 6 and 7, consistent with −T-directed streaming along the average azimuthal orientation of the magnetic field in the heliosheath.

Table 1 | Voyager 1 roll periods, fit coefficients and heliosheath plasma flow velocities

Roll period	No. rolls	C_0 ($\times10^{-1}$ cnt s^{-1})	A_1 ($\times10^{-2}$)	B_1 ($\times10^{-2}$)	ξ_1 ($\times10^{-2}$)‡	ϕ_1 (°)‡	γ	V_R (km s^{-1})	V_N (km s^{-1})
1: 2011/066–073 (March 2011)	6 (21 h)*	1.97 ± 0.05 (890)†	−6.54 ± 3.78	−0.20 ± 2.94	6.54 ± 3.77	159 ± 26	1.55	−26.0 ± 25.8 (28,858 s)§	−16.3 ± 21.7
2: 2011/121–131 (May 2011)	7 (25 h)	1.65 ± 0.04 (819)	−3.81 ± 4.03	−4.37 ± 3.13	5.80 ± 3.54	206 ± 36	1.52	−19.8 ± 27.8 (34,474 s)	+18.4 ± 23.3
3: 2011/207–217 (July 2011)	6 (20 h)	1.58 ± 0.05 (631)	−2.53 ± 4.65	−4.67 ± 3.62	5.32 ± 3.88	219 ± 48	1.48	−12.7 ± 32.6 (27,821 s)	+24.2 ± 27.4
4: 2011/302–307 (October 2011)	6 (10 h)	1.32 ± 0.07 (254)	−3.88 ± 7.87	0.95 ± 6.13	4.00 ± 7.78	144 ± 90	1.44	−6.5 ± 56.1 (13,306 s)	−17.3 ± 47.1
5: 2012/016–030 (January 2012)	7 (10 h)	1.74 ± 0.07 (343)	−1.24 ± 6.18	2.42 ± 4.73	2.73 ± 5.06	94 ± 124	1.40	+15.5 ± 44.0 (13,824 s)	−20.2 ± 37.0
Time-weighted average	—	—	—	—	—	—	—	−14.0 ± 13.6‖	+2.8 ± 11.4

* Number of hours of data taken during rolled configuration that were used in (V_R, V_N) analysis.
† Mean number of counts per sector for the seven active sectors of the Low-Energy Charged Particle instrument.
‡ First-order anisotropy amplitude $\xi_1 = (A_1^2 + B_1^2)^{1/2}$ and associated azimuth angle $\phi_1 = \tan^{-1}(B_1/A_1)$ (Fig. 3a).
§ Total data accumulation time of data used in flow velocity determination; used to perform weighted average in row 6.
‖ Mean values of V_R and V_T determined from data taken during 2011/066–2012/030 are $V_R = -6.5 \pm 4.1$ km s^{-1} and $V_{T'} = -25.8 \pm 3.8$ km s^{-1}.

A least-squares solution yields the amplitudes and phases of the first two harmonics. We assume that ions have an isotropic intensity $j \propto E^{-\gamma}$ in a frame moving with the heliosheath flow. The instrument measures the spectral slope (γ) in adjacent energy (E) channels. The well-known theory of the Compton–Getting effect[4] relates the components of the convective flow (V_R, V_N) in the scan plane to the coefficients of the first harmonic anisotropy through the spectral slope and ion speed (v):

$$A_1 = 2(\gamma+1)(V_R/v), \qquad B_1 = 2(\gamma+1)(V_N/v) \qquad (2)$$

We have calibrated our fitting procedure by comparison with the V_R and V_T components of plasma flow measured by Voyager 2 in the heliosheath using the Plasma Science instrument[5] (Fig. 2), which directly measures the solar wind velocity. The Plasma Science instrument on Voyager 1 failed in 1980. The comparison in Fig. 2 shows that, with the exception of periods of weak field-aligned ion streaming that we can readily identify in both the Voyager 2 and Voyager 1 data, the velocities derived from directional intensities of low-energy ions by the method described above is able to reproduce the solar wind velocity components quite well in the Low-Energy Charged Particle Instrument's scan plane. This justifies a posteriori our assumption that the particle distribution function is essentially isotropic in the plasma frame.

Orientations of the scan plane in its usual and rolled configuration are shown in Fig. 3a, b. The results of our Fourier analysis of the five Voyager 1 roll periods are presented in Fig. 3c–g. Figure 3h shows the intensities of 53–85-keV heliosheath protons arriving from the sunward and anti-sunward directions. The roll period dates, numbers of rolls per period and fit coefficients (C_0, A_1 and B_1) are given in columns 1–5 of Table 1. The errors in C_0, A_1 and B_1 are determined by propagating the Poisson statistical uncertainties in the sectored counting rates, which are shown as vertical error bars ($\pm1\sigma$) about the mean in Fig. 3c–g, using the equations that express C_0, A_1 and B_1 as functions of the sectored rates. Alternative representations of A_1 and B_1 in terms of the first-order anisotropy amplitude ξ_1 and azimuth ϕ_1 are given in columns 6 and 7 of Table 1, and the spectral power-law index γ is in column 8. The plasma convection velocity components V_R and V_N (columns 9 and 10) implied by the first harmonic are given along with their uncertainties, which are calculated by propagating the errors in fit coefficients C_0, A_1 and B_1 using equation (2). The time-weighted averages of V_R and V_N over all five rolls are summarized in row 6 of those two columns. The five determinations of V_N in the rolled configuration are plotted in Fig. 3j along those of V_R and $V_{T'}$, the latter two components calculated using 26-d-averaged ion angular data taken in the usual (unrolled) configuration.

The averages of the velocity components and their uncertainties derived from the five roll periods are $\langle V_R \rangle = -14 \pm 14$ km s^{-1} and $\langle V_N \rangle = +3 \pm 11$ km s^{-1}. The negative mean radial velocity during the rolls is consistent within errors with the more statistically significant result (-6.5 ± 4.1 km s^{-1}) from the 26-d averages spanning the five roll periods in Fig. 3i, j (filled circles). The 26-d averages of the azimuthal flow ($V_{T'}$) have a larger and statistically significant negative value (-25.8 ± 3.8 km s^{-1}). Although azimuthal flow is not the topic of this report, we do not wish its clear signature to pass unnoticed.

We offer several arguments that the time-weighted average for V_N over five rolls is statistically consistent with zero, and moreover that it is small in an absolute sense. First, if our measurements of V_N are consistent with zero, we would expect that roughly half of our roll period measurements would have $V_N > 0$ and half would have $V_N < 0$. Over the five spacecraft rolls, two had $V_N > 0$ and three had $V_N < 0$. Second, the Poisson error bars for each roll always bracket zero, giving no indication of a systematic non-zero flow. Third, as the Poisson distribution can be approximated by a Gaussian because the number of counts accumulated in each sector exceeds 250 (Table 1, column 3), our five-roll result $\langle V_N \rangle = +3 \pm 11$ km s^{-1} implies only a 16% probability that $\langle V_N \rangle$ exceeds $+14$ km s^{-1}. For comparison, the distant upstream flow velocity of the local interstellar medium is $\sim$25 km s^{-1}. The solar radial vector to Voyager 1 is $\sim$30° offset from the upstream flow direction, that is, from the expected 'nose' of the heliosheath. At this angle, most steady-state models show a positive meridional flow that within the heliosheath is a significant fraction of the distant upstream value or even exceeds it (because of the constriction of plasma streamlines as they divert around the heliosheath). Our results give us 84% confidence that $\langle V_N \rangle$ is less than half of the distant upstream flow, even though our error bars are larger than our mean velocity (3 ± 8 km s^{-1}). This is a drastic difference from the steady-state predictions.

We therefore conclude from our values (3 km s$^{-1} \ll$ 25 km s^{-1}) that Voyager 1 is not at present close to the heliopause, at least in the form that it has been envisioned up to now. In fact, it has been in the transition region of weak radial (V_R) flow for over two years now (Fig. 3j), during which time it travelled an additional 7.5 AU outwards from the Sun. We do not know how much farther outwards the transition region extends, and the longer it lasts in time, the less likely it is to be dominated by a temporal effect of the expansion and contraction of the heliopause during the 11-year solar activity cycle[3]. However, a non-stationary solar wind should be included in any realistic model. In any case, any theories that predict a meridional flow velocity significantly outside of the Voyager 1 statistical limits (-8 km s$^{-1} < \langle V_N \rangle <$ 14 km s^{-1}) should be reassessed, perhaps necessitating a new theoretical formulation of the interaction of the solar wind with the local interstellar medium.

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1. Krimigis, S. M., Roelof, E. C., Decker, R. B. & Hill, M. E. Zero outward flow velocity for plasma in a heliosheath transition layer. *Nature* **474,** 359–361 (2011).
2. Pogorelov, N. V., Borovikov, S. N., Zank, G. P. & Ogino, T. Three-dimensional features of the outer heliosphere due to coupling between the interstellar and interplanetary magnetic fields. III. The effects of solar rotation and activity cycle. *Astrophys. J.* **696,** 1478–1490 (2009).

3. Borovikov, S. N., Pogorelov, N. V., Burlaga, L. F. & Richardson, J. D. Plasma near the heliosheath: observations and modeling. *Astrophys. J.* **728,** L21–L26 (2011).
4. Gleeson, L. J. & Axford, W. I. The Compton-Getting effect. *Astrophys. Space Sci.* **2,** 431–437 (1968).
5. Richardson, J. D. & Wang, C. Plasma in the heliosheath: 3.5 years of observations. *Astrophys. J.* **734,** L21–L24 (2011).

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