

# Accretion of low-metallicity gas by the Milky Way

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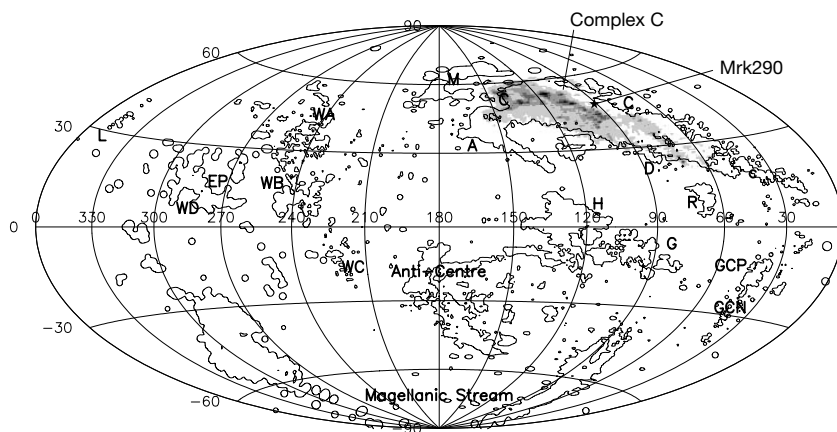
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Models of the chemical evolution of the Milky Way suggest that the observed abundances of elements heavier than helium ('metals') require a continuous infall of gas with metallicity (metal abundance) about 0.1 times the solar value. An infall rate integrated over the entire disk of the Milky Way of ~1 solar mass per year can solve the 'G-dwarf problem'—the observational fact that the metallicities of most long-lived stars near the Sun lie in a relatively narrow range<sup>1–3</sup>. This infall dilutes the enrichment

arising from the production of heavy elements in stars, and thereby prevents the metallicity of the interstellar medium from increasing steadily with time. However, in other spiral galaxies, the low-metallicity gas needed to provide this infall has been observed only in associated dwarf galaxies<sup>4</sup> and in the extreme outer disk of the Milky Way<sup>5,6</sup>. In the distant Universe, low-metallicity hydrogen clouds (known as 'damped Ly $\alpha$  absorbers') are sometimes seen near galaxies<sup>7,8</sup>. Here we report a metallicity of 0.09 times solar for a massive cloud that is falling into the disk of the Milky Way. The mass flow associated with this cloud represents an infall per unit area of about the theoretically expected rate, and ~0.1–0.2 times the amount required for the whole Galaxy.

Our result is based on spectra of the Seyfert galaxy Markarian 290, which samples the high-velocity cloud (HVC), complex C (ref. 9). High-velocity clouds consist of neutral hydrogen moving at velocities incompatible with a simple model of differential galactic rotation<sup>9</sup>. Complex C is approaching the Sun at ~150 km s<sup>-1</sup>. Assuming the tangential velocity is not extremely large, complex C appears to be falling towards the Galactic plane at 50–100 km s<sup>-1</sup>, after correcting for differential galactic rotation. Figure 1 presents an all-sky map of the HVCs, with complex C highlighted. The spectra are collected in Fig. 2.

S II absorption associated with complex C was observed using the Goddard High Resolution Spectrograph on the Hubble Space Telescope. S<sup>+</sup> provides a good measure of the intrinsic metallicity of a hydrogen cloud, as sulphur is one of a few elements in the interstellar medium not depleted onto dust, while S<sup>+</sup> is the domi-



**Figure 1** All-sky map of the high-velocity clouds (HVCs) in Aitoff projection, from 21-cm surveys<sup>9</sup>. HVCs consist of gas moving at velocities incompatible with a simple model of differential galactic rotation. The Galactic equator runs through the middle, the Galactic anti-centre is in the centre of the plot. The contour level is at a hydrogen column density of

$2 \times 10^{18} \text{ cm}^{-2}$ . The names of the main complexes (from ref. 9) are indicated. HVC complex C is highlighted; the darkest pixels correspond to a column density of  $1 \times 10^{20} \text{ cm}^{-2}$ . The position of Markarian 290 is indicated (Mrk290).

**Table 1** Systematic errors in the determination of the sulphur abundance

Effect	Relevant observational quantity	Observed value	Possible range	Difference in derived abundance
Geometry	See below			-0.012 to +0.000
Temperature	$I(\text{S II})/I(\text{H}\alpha)$	0.03	0.10–0.01	-0.003 to +0.002
Saturation	FWHM (km s <sup>-1</sup> )	15	14–10	-0.000 to +0.009
Ionization	$N(\text{S}^{2+})/N(\text{S}^+)$ in H <sup>+</sup> region	0.5	0.0–0.7	-0.006 to +0.003
H $\alpha$ fine structure	$I(\text{H}\alpha)$ (Rayleigh)	0.187	0.094–0.280	-0.003 to +0.004
Component structure	$N(\text{H I})$ (10 <sup>18</sup> cm <sup>-2</sup> )	92	92–53	-0.000 to +0.060
Distance	$D$ (kpc)	10	25–5	-0.009 to +0.004
Add linearly				-0.033 to +0.082
Add in quadrature (=3 $\sigma$ )				-0.017 to +0.061

The geometry is usually assumed to be a neutral core and ionized envelope with constant density. Alternatives include a gaussian density profile in the line-of-sight and/or constant partial ionization. A full width at half-maximum (FWHM) of 10 km s<sup>-1</sup> is the minimum line width consistent with the equivalent width errors. S<sup>2+</sup> only occurs where hydrogen is ionized; in diffuse ionized gas the ratio  $N(\text{S}^{2+})/N(\text{S})$  is typically <~0.5 (ref. 27). Si  $\lambda$ 1262.86 is not detected, yielding a lower limit  $N(\text{S}^+)/N(\text{S, tot}) > 0.4$ ; however, S<sup>+</sup> has low abundance in the diffuse ISM<sup>10</sup>, as it has a low ionization potential (10.4 eV). The possible range in H $\alpha$  emission allows for structure on small angular scales. The largest uncertainty is associated with the component structure, as the S II spectrum does not show separate absorptions at the velocities of the two H I components. If the S II absorption were only associated with the ~138 km s<sup>-1</sup> H I component (and if we associate half of the H $\alpha$  emission with it), the implied sulphur abundance would be 0.15 times solar. The final systematic error is calculated by summing in quadrature the maximum changes associated with the listed effects. Even if all systematic effects were to work in the same direction, the sulphur abundance must still be in the range 0.06–0.17 times solar to be compatible with the measurements.

nant ionization stage in neutral and weakly photoionized gas<sup>10</sup>, such as exists in complex C. It is assumed that the heavy elements occur in the same proportions in the HVC as in stars. Previously, only depleted elements had been observed in HVCs<sup>9</sup>, except in one cloud which is associated with the Magellanic stream<sup>11</sup> and not currently falling in.

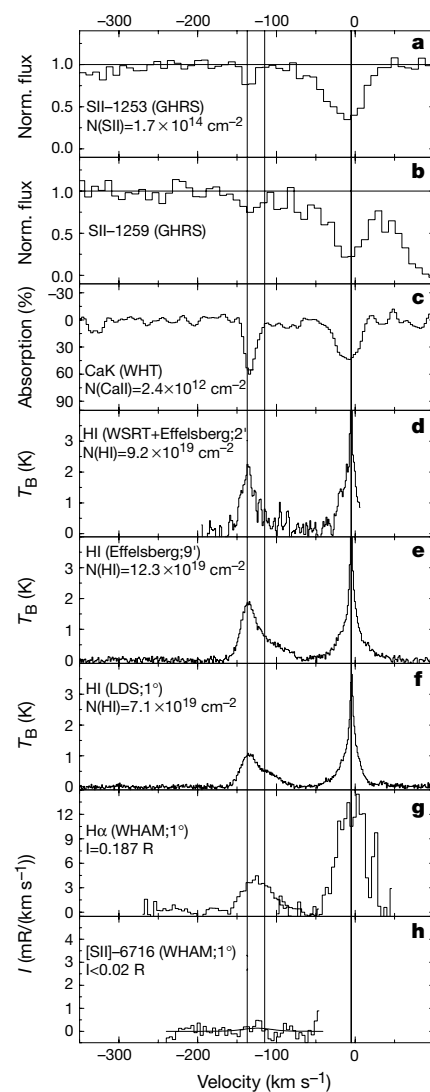
A good abundance determination requires as a reference the total (neutral plus ionized) hydrogen column density. As the S II absorption takes place in a pencil-beam path through the HVC, the hydrogen should be measured at the highest-possible angular resolution. The neutral component was found by combining data from the Westerbork Synthesis Radio Telescope (WSRT; 2' beam) and the Effelsberg telescope (9' beam). Figure 2d shows the combined spectrum, Fig. 2e shows the Effelsberg spectrum separately. H $\alpha$  emission from ionized hydrogen was observed using the Wisconsin H $\alpha$  Mapper (WHAM<sup>12</sup>; Fig. 2g), although only at 1° resolution. To determine the average ionized fraction, an H I spectrum at 1° resolution was created by averaging four spectra from the Leiden-Dwingeloo survey<sup>13</sup> (Fig. 2f). We also used WHAM to set a limit to the [S II] 6,716 Å emission line (Fig. 2h).

We derive physical parameters by assuming a distance and a geometry, that is, a density and ionization structure in the sightline. Using the intensity ratio  $I([S II])/I(H\alpha)$  to estimate the temperature then allows us to convert the H $\alpha$  emission measure to an H<sup>+</sup> column density<sup>14</sup>. We find a sulphur abundance  $A(S) = 0.089 \pm 0.024^{+0.020}_{-0.005}$  times the solar value<sup>15</sup>, a total hydrogen density  $n = 0.08 \pm 0.01 (D/10 \text{ kpc})^{-0.5} \text{ cm}^{-3}$ , an ionization fraction  $N(H^+)/N(H, \text{tot}) = 17 \pm 5^{+7}_{-1} \%$ , a temperature  $T = 7,300 \pm 900^{+1,500}_{-1,000} \text{ K}$ , and a thermal pressure  $P = 580 \pm 130 \pm 130 (D/10 \text{ kpc})^{-0.5} \text{ K cm}^{-3}$ . Here,  $D$  is the distance to the cloud. The first  $1\sigma$  error comes from the statistical error in the observations. The second is the  $1\sigma$  systematic error, as summarized in Table 1.

To show that complex C is associated with the Milky Way requires an estimate of its distance. We have derived a lower limit<sup>16</sup> of 5 kpc (that is, >3 kpc above the Galactic disk). A definite upper limit is not known, but plausible arguments can be made that complex C is relatively nearby. First, it has large angular size (20° × 90°). Second, if the H<sup>+</sup> is produced by high-energy photons escaping the disk, then H $\alpha$  brightness is a measure of height above the Galactic plane. Complex C has an H $\alpha$  brightness comparable to that of another HVC which has a distance of 4–10 kpc (ref. 17). Third, we can assume pressure equilibrium between hot gas in the Galactic halo and the HVC, deriving the external pressure from the observed temperature and density of the X-ray halo<sup>18</sup>, combined with a semi-empirical halo model<sup>19</sup>. This yields 7 kpc, but up to 25 kpc is compatible with  $1\sigma$  errors on the parameters. We note that for a velocity of 50–100 km s<sup>-1</sup> relative to the surrounding halo gas (below the sound speed of ~120 km s<sup>-1</sup> at  $T = 10^6 \text{ K}$ ), the ram pressure is a factor of 7–2 less than the thermal pressure.

We derive a mass of  $6.2 \times 10^6 (D/10 \text{ kpc})^2 M_\odot$  for complex C (where  $M_\odot$  is the solar mass), assuming no molecular hydrogen<sup>20</sup>, constant  $N(H^+)/N(H, \text{tot})$ , and a 28% mass fraction of helium. Using the possible range of its vertical velocity, and dividing the mass by the time to impact gives an associated mass flow of 0.002–0.004 (D/10 kpc)<sup>-1</sup> M $\odot$  yr<sup>-1</sup> kpc<sup>-2</sup>, or 0.08–0.19 (D/10 kpc) M $\odot$  yr<sup>-1</sup>. To solve the G-dwarf problem, models require an inflow of gas with one-tenth solar metallicity at a current rate<sup>2</sup> of 0.004 M $\odot$  yr<sup>-1</sup> kpc<sup>-2</sup>, similar to the rate associated with complex C. To get the required total infall of ~1 M $\odot$  yr<sup>-1</sup>, there should be 5–10 (D/10 kpc)<sup>-1</sup> similar objects around the Milky Way; several other HVCs are obvious candidates (see Fig. 1).

Given the position, velocity and metallicity of complex C, what can we say about its origin? It is not possible that it originated in the Galactic disk at galactocentric distances less than about 15 kpc (the Sun is at 8 kpc), as part of a Galactic fountain<sup>21</sup>. In that case, near-solar metallicity is expected. It is also unlikely that it originated in the outer disk. The lowest observed sulphur abundance there is 0.11



**Figure 2** Spectra on or centred on Markarian 290, aligned in velocity. Vertical lines are drawn at velocities (km s<sup>-1</sup>) of -138, -115 and 0 relative to the local standard of rest (LSR). The first two components belong to the HVC, complex C, whereas the low-velocity component corresponds to gas near the Sun; the HVC approaches about 100 km s<sup>-1</sup> faster than can easily be understood from differential galactic rotation. Panels **a** and **b** show two of the three S II absorption lines, observed with the Goddard High-Resolution Spectrograph (GHRS), after normalization to the continuum (15 km s<sup>-1</sup> velocity resolution; the 1,250 Å line is confused with absorption intrinsic to Markarian 290. Equivalent widths were converted to column density using the best  $f$ -values, and assuming an intrinsic full-width at half-maximum (FWHM) of 15 km s<sup>-1</sup> based on the resolved Ca II lines. The values for the 1,253 and 1,259 Å lines were weighted by the signal-to-noise ratio in the continuum to derive  $N(S^+) = (1.68 \pm 0.35) \times 10^{14} \text{ cm}^{-2}$ . **c**, Ca II spectrum observed with the William Herschel Telescope (WHT), from ref. 13, at 6 km s<sup>-1</sup> velocity resolution. **d–f**, HI spectrum observed with different beams, at 1 km s<sup>-1</sup> velocity resolution. The 2' spectrum (**d**) yields  $N(HI) = (91.7 \pm 7.2) \times 10^{18} \text{ cm}^{-2}$  toward Mrk290, the 9' spectrum (**e**) shows the component structure, while the 1° spectrum (**f**,  $N(HI) = (70.6 \pm 4.0) \times 10^{18} \text{ cm}^{-2}$ , from the Leiden-Dwingeloo Survey, LDS) is compared to the H $\alpha$  data to derive the ionization fraction. **g**, H $\alpha$  spectrum (12 km s<sup>-1</sup> velocity resolution, observed with the Wisconsin H $\alpha$  Mapper, WHAM), showing an HVC intensity of  $0.187 \pm 0.01 \text{ R}$  (1 rayleigh is  $10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ). This combines separate 20-min ( $v < -50 \text{ km s}^{-1}$ ) and 30-s ( $v > -100 \text{ km s}^{-1}$ ) integrations; the feature at about +20 km s<sup>-1</sup> is fixed-pattern noise. **h**, [S II] 6,716 of spectrum (12 km s<sup>-1</sup> velocity resolution), in which the HVC is not detected, overlaid with a curve for which  $I([S II])/I(H\alpha) = 0.03$ . We derive a limit  $I([S II])/I(H\alpha) < 0.1 (3\sigma)$ . For Galactic disk gas with solar abundances, this ratio is typically ~0.3, with a minimum of ~0.2 (ref. 27). Since for complex C the ratio  $N(S^+)/N(H^+)$  is ~0.1 solar, an emission ratio ~0.03 is expected, consistent with our non-detection.

times solar<sup>5</sup>, but to move  $\sim 10^7 M_{\odot}$  of gas inward and to a position  $>3$  kpc above the disk requires more energy than seems available.

A number of authors (see ref. 9 for an overview), have proposed that the Local Group (a cluster of galaxies, of which our Galaxy is a member) is filled with hydrogen clouds with typical hydrogen masses of  $10^7 M_{\odot}$ . Adding large amounts of dark matter (10 times as much mass as in hydrogen) could make such clouds stable<sup>22</sup>. In the early universe, these mini-galaxies would pick up heavy elements from the then-nearby large galaxies as the latter vigorously formed stars. Complex C could be such an object, whose orbit brought it close to the Milky Way at the present time. A problem with this model is that similar clouds were not detected in other galaxy groups during a sensitive survey done at Arcicob<sup>23</sup>.

A more probable origin was proposed by Oort<sup>24</sup>, who argued that the Milky Way is still forming. In this model, much gas was left over after the Milky Way's original formation, and this gas slowly accretes over time. Complex C (and a few other HVCs) would be among the few still-to-be-accreted objects. Its heavy-element content is then understood as a contamination created after it started interacting with gas in the Galactic halo.

Alternatively, HVCs like complex C may consist of gas tidally stripped from nearby dwarf galaxies when the latter's orbit brought them near the Milky Way. The heavy elements would then have been formed in the dwarf. These dwarfs could subsequently have evolved into the present dwarf spheroidal galaxies<sup>25</sup>, or their stars might have merged with those of the Milky Way. That such processes still operate is shown by the presence of the Magellanic stream<sup>26</sup>, a tidal tail torn out of the Small Magellanic Cloud 2 Gyr ago. Combining the theoretical understanding of the chemical evolution and formation of the Milky Way with the constraints set by observations of other galaxy groups, the current content of the Local Group as well as the position, velocity and metallicity of complex C, we conclude that rather than having been assembled in the early universe, it is more probable that the formation of the Milky Way is still continuing. This is fed by gas either left over from the original formation of the Milky Way or stripped from Local Group dwarf galaxies. □

Received 14 June; accepted 4 October 1999.

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## Acknowledgements

This work was supported by the Space Telescope Science Institute. The Hubble Space Telescope is operated by the Association of Universities for Research in Astronomy, Inc. The Effelsberg Telescope belongs to the Max Planck Institute for Radio Astronomy in Bonn. The Westerbork Radio Observatory is operated by the Netherlands Foundation for Research in Astronomy (ASTRON/NFRA) with financial support from NWO.

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## Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations

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Algorithms such as quantum factoring<sup>1</sup> and quantum search<sup>2</sup> illustrate the great theoretical promise of quantum computers; but the practical implementation of such devices will require careful consideration of the minimum resource requirements, together with the development of procedures to overcome inevitable residual imperfections in physical systems<sup>3–5</sup>. Many designs have been proposed, but none allow a large quantum computer to be built in the near future<sup>6</sup>. Moreover, the known protocols for constructing reliable quantum computers from unreliable components can be complicated, often requiring many operations to produce a desired transformation<sup>3–5,7,8</sup>. Here we show how a single technique—a generalization of quantum teleportation<sup>9</sup>—reduces resource requirements for quantum computers and unifies known protocols for fault-tolerant quantum computation. We show that single quantum bit (qubit) operations, Bell-basis measurements and certain entangled quantum states such as Greenberger–Horne–Zeilinger (GHZ) states<sup>10</sup>—all of which are within the reach of current technology—are sufficient to construct a universal quantum computer. We also present systematic constructions