Conf. Milky Way Halo, Bonn 2007, Poster 6

The Ophiuchus Superbubble: A Gigantic Disk-Halo Transition Phenomenon

Y. Pidopryhora (JIVE); F. J. Lockman (NRAO); J. C. Shields (Ohio Univ.)

Abstract

We have discovered what appears to be a huge superbubble centered around $\ell \sim 30^{\circ}$, whose top extends to latitudes $>25^{\circ}$ at a distance of about 7 kpc. It is detected in both HI and Hα. Using 100m Green Bank Telescope (GBT), we have measured about quarter of a million HI spectra at 9′ angular resolution in and around this structure. The total HI mass of it is about one million solar masses and it has an equal mass in H^+. The kinematics of the plume of HI capping the top of the superbubbble at the height of about 3.4 kpc appears to be dominated by Galactic rotation, but with a lag of 27 km s^{-1} from corotation. At the base of the superbubble there are "whiskers" of HI several hundreds of parsecs wide, reaching more than 1 kpc into the halo; they have a vertical density structure suggesting that they are the bubble walls and have been created by sideways rather than upward motion. From a Kompaneets model of an expanding bubble, we estimate that the age of this system is ~30 Myr and its total energy content $\sim 10^{53}$ ergs. This system offers an unprecedented opportunity to study Galactic disk-halo interaction at close range.

Contact Information:

Y. Pidopryhora
pidopryhora@jive.nl
Joint Institute
for VLBI in Europe
Postbus 2
7990 AA Dwingeloo
The Netherlands

F.J. Lockman
jlockman@nrao.edu
National Radio
Astronomy Observatory
P.O. Box 2
Rt. 28/92
Green Bank, WV 24944
USA

J.C. Shields
shields@phy.ohiou.edu
Dept. of Physics & Astronomy
Ohio University
Clippinger Lab 251B
Athens, OH 45701
USA

The Robert C. Byrd Green Bank Telescope at sunrise.
Photo courtesy of NRAO/AUI and Harry Morton (NRAO)

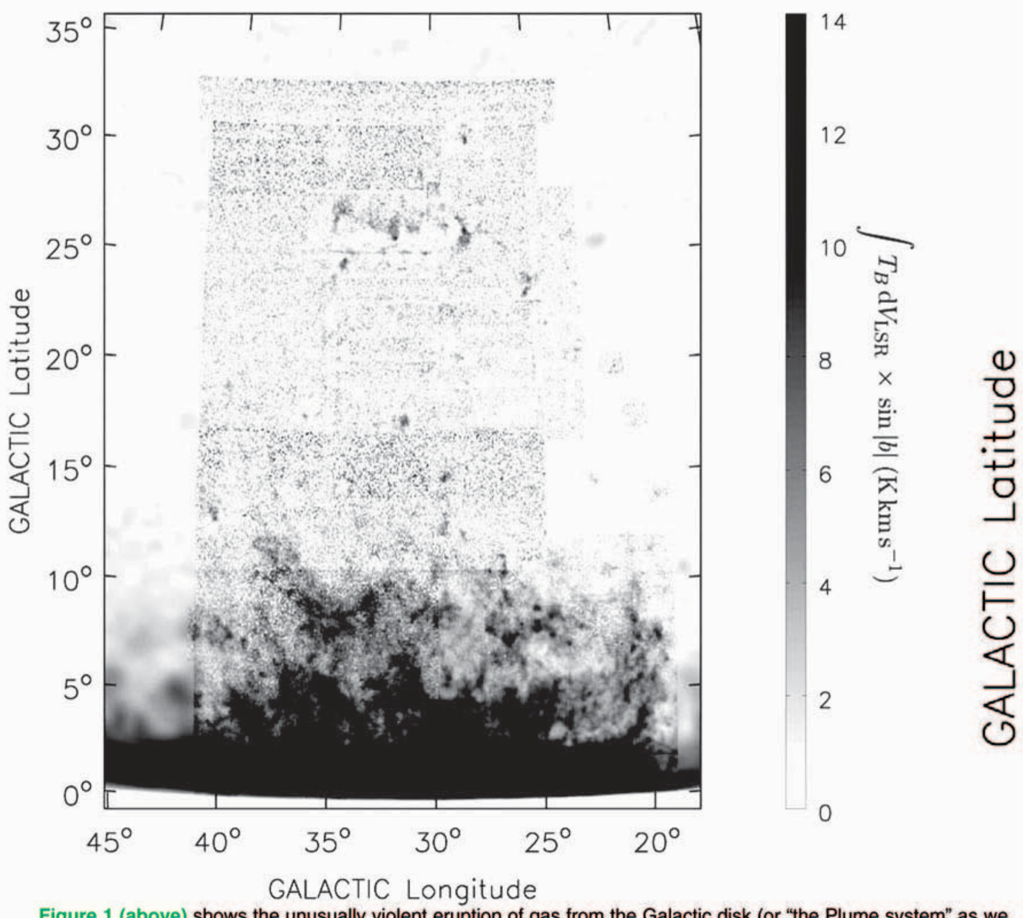

Figure 1 (above) shows the unusually violent eruption of gas from the Galactic disk (or "the Plume system" as we call it because of the cap on top of it, "the Plume") in HI. HI spectra integrated over $60 \le V_{LSR} \le 160$ km s^{-1} show the system in the context of the Galactic disk and lower halo. The integration covers all the tangent point velocities at these longitudes. GBT HI spectra are used for most of the map, but data from the lower resolution Leiden-Dwingeloo survey (Hartmann & Burton 1997) are used around the edges. The intensity scale has been multiplied by sin |b| to compress the dynamic range and show structures more clearly. Several coherent HI features (we dub them "whiskers") stretch from the disk to $b \ge 15^{\circ}$ ($z \approx 2$ kpc). Dozens of compact but relatively dense clouds fill the space between the whiskers and the Plume.

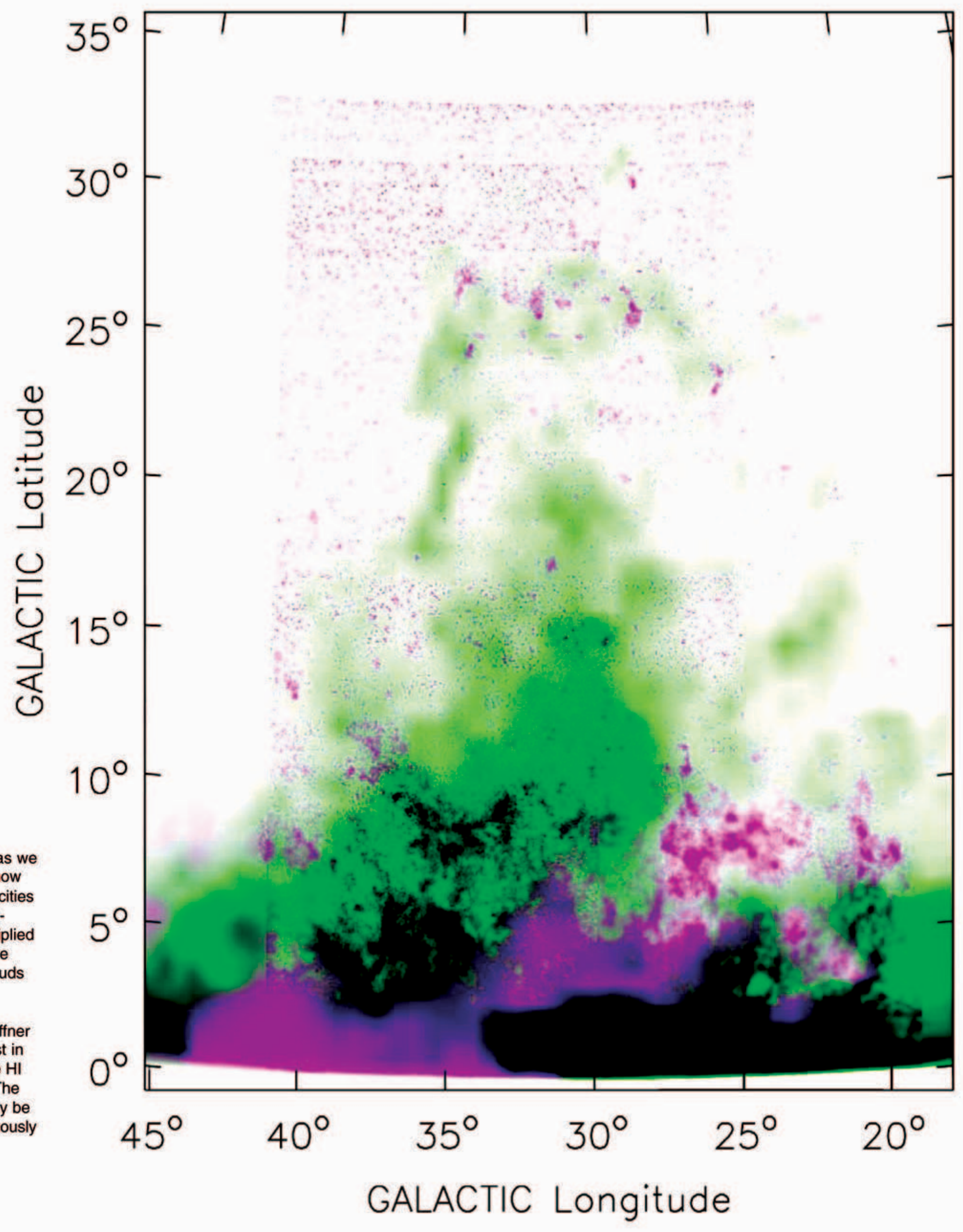

Figure 2 (right) shows the HI data from Figure 1 (purple) with interpolated H α data from WHAM survey (Haffner et al. 2003) added (green). The diagonal purple stripe at the bottom results from extinction of the H α by dust in the Great Rift. There is detailed correspondence between HI and H α for many features, e. g., the tips of the HI whiskers at $l,b \approx 40^{\circ} + 15^{\circ}$ and $30^{\circ} + 15^{\circ}$, clouds at $29^{\circ} + 31^{\circ}$ and $22^{\circ} + 25^{\circ}$, and indeed, the Plume itself. The ionized components of some of the smaller clouds appear shifted to higher longitude than the HI, but this may be the effect of the sparsity of the H α survey and its 1° beam size. The H α emission connects the Plume continuously to the Galactic disk and thus suggests that this system is a singular phenomenon of gigantic proportions.

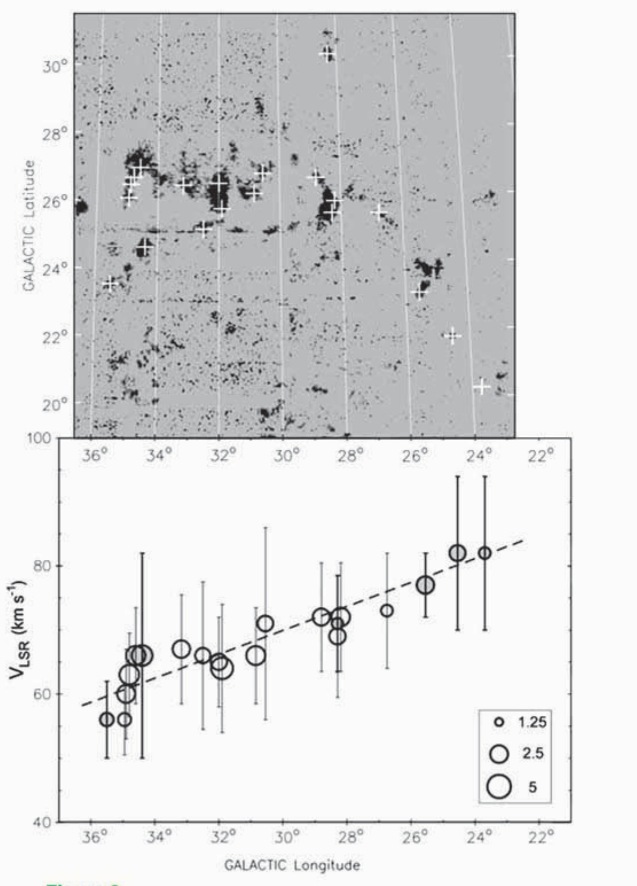

Figure 3
Kinematics of the Plume in relation to its spatial structure. The lower part of the figure shows the velocity of all of the clearly discernable features of the Plume (marked by crosses in the upper panel). The area of each circle is proportional to log $N_{HI} - 19$, where N_{HI} is the column density in cm^{-2}; the legend shows circle sizes for a few values of N_{HI} in units of 10^{19} cm^{-2}. The bar through each point shows the FWHM of the line. The dashed line is a linear fit to the CO terminal velocity measurements in the Galactic plane (Clemens 1985) with an offset illustrated by Figures 5 and 6. It shows that the linear dependence of LSR velocity with longitude is fully explained by Galactic rotation and projection effects. Measurements made above or below the main section of the Plume at $25^{\circ} < b < 28^{\circ}$ are filled with gray and have bolder bars, and show that the coherence of the structure extends even to outlying clouds.

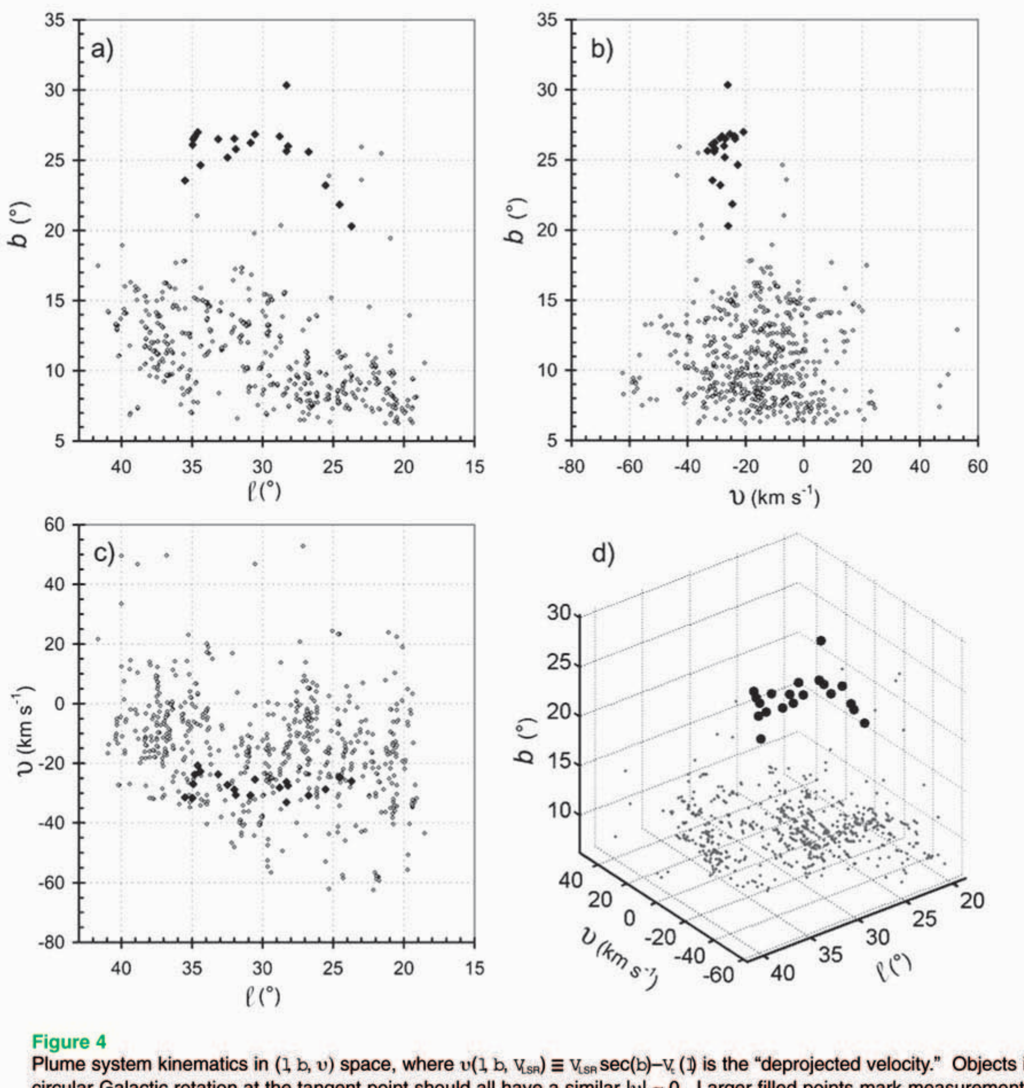

Figure 4
Plume system kinematics in (l, b, υ) space, where $\upsilon(l, b, V_{LSR}) \equiv V_{LSR}\sec(b) - V_t(l)$ is the "deprojected velocity." Objects in circular Galactic rotation at the tangent point should all have a similar $|\upsilon| \approx 0$. Larger filled points mark measurements on the Plume itself, the same set shown in Figure 3. Panels a) through c) show three 2D projections and panel d) a 3D plot of the same data. The Plume is kinematically compact compared to other parts of the Plume system and has a slight velocity offset. Coherent chains of features of constant $\upsilon \approx$ -45, -35 and -10 km s^{-1} seen in panel b), reaching to the Plume's latitude, may be other parts of the system, like the front and the back walls of the superbubble..

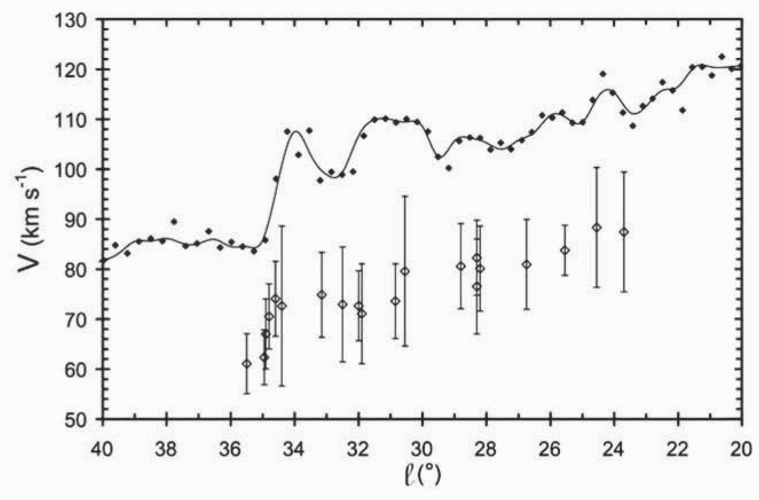

Figure 5 (above)
Velocity structure of the Plume compared to that of the plane gas. The filled points are measurements of the ^{12}CO terminal velocity in the Galactic plane (Clemens 1985). The curve is a cubic spline interpolation fit to the median filtered ^{12}CO velocities. The open symbols show the Plume's HI velocity, $V_{LSR}\sec(b)$, and the vertical bars show the line FWHM. The Plume traces the CO kinematics, but with an offset.

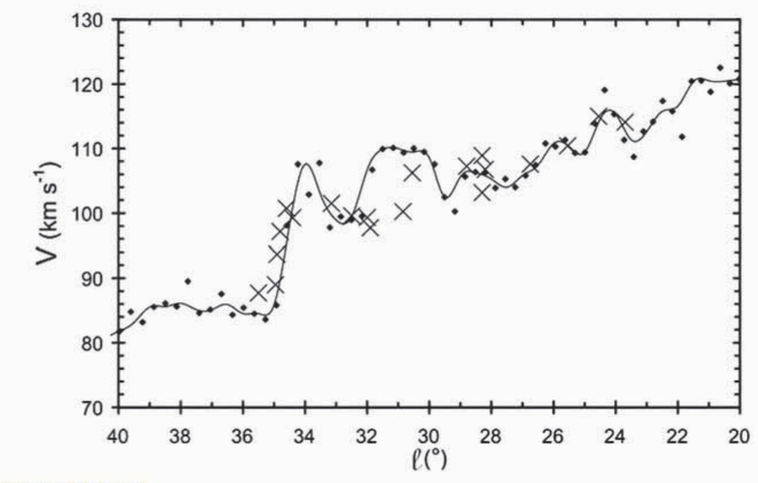

Figure 6 (below)
Velocity structure of the Plume, compensated for lag, compared with that of the plane gas. These are the same data as in Fig. 5, but with the HI velocities (marked here with crosses) increased by 26.6 km s^{-1}. The close agreement of these measurements shows that the Plume shares the same kinematics as molecular clouds in the Galactic plane, even in considerable detail. The Plume kinematics are thus dominated by Galactic rotation.

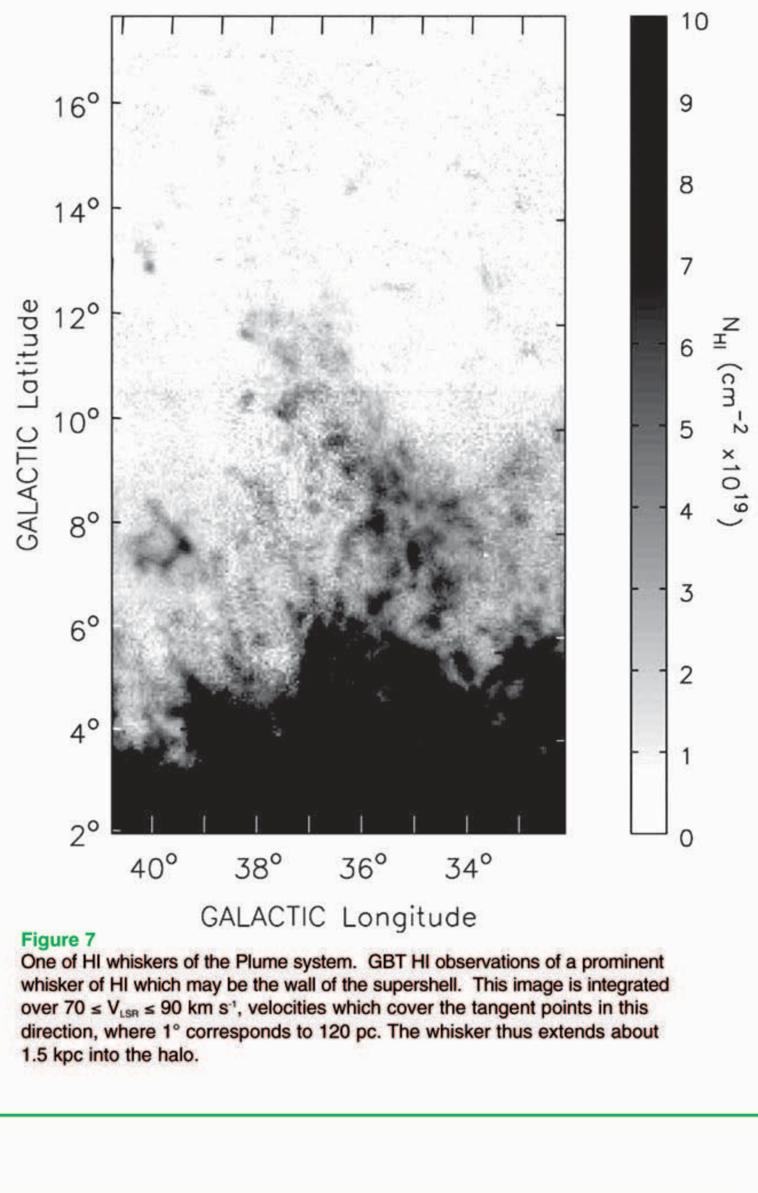

Figure 7
One of HI whiskers of the Plume system. GBT HI observations of a prominent whisker of HI which may be the wall of the supershell. This image is integrated over $70 \le V_{LSR} \le 90$ km s^{-1}, velocities which cover the tangent points in this direction, where 1° corresponds to 120 pc. The whisker thus extends about 1.5 kpc into the halo.

Summary Comments

The system of ionized and neutral gas shown here lies in the inner Galaxy over several spiral arms which are sites of active star formation. Despite its size, the system can be created and maintained by stellar clusters like the one currently powering the HII region W43.

Kompaneets model fit to the data indicates that we are seeing either the late stages of the bubble's development or the early stages of its decomposition. The irregular structure and broad lines of the HI cap on the system suggests substantial turbulent motions. Overall, though, the kinematics of the cap matches the kinematics of molecular clouds in the plane below it, though with a lag of 27 km/s. Extra-planar gas is expected to show a gradient in rotational velocity arising from a change in the gravity vector with z, and this has been observed in other galaxies, but previously not convincingly in the Milky Way.

At the base of the system there are a number of HI 'whiskers' extending several kpc into the halo. We think that some are likely to be the swept-up walls of this or other superbubbles. They resemble the vertical lanes seen in dust absorption by the WIYN telescope against the light of the edge-on galaxy NGC 891 (Howk & Savage 2000) and not so much the vertical structures seen in Galactic HI usually attributed to outflows (Heiles 1984; English et al. 2000).

The system described here seems to be a typical old superbubble given its size of ~2 kpc, age of ~30 Myr and the lack of detectable expansion or vertical motion in the cap. Its total mass of a few million solar masses, and its energy of log(E)=53 ergs are also typical of bubbles of this size. But its large size is unusual for the small galactocentric distance of just 4 kpc; it is at least twice as large as any known HI bubble at a similar location in the Galaxy (McClure-Griffiths et al 2002). Creation of such superbubbles should be commonplace in Galactic spiral arms, and perhaps it is simply the enormous angular extent of this system (>500 square degrees) and low surface brightness of its top that has prevented its detection until now. Also, one needs an independent nearby stellar cluster to ionize the system after its parent cluster is dead.

Our understanding of this system is just beginning. It is ideally placed for further study. Measurements in UV absorption lines might allow us to study its internal structure and search for abundance anomalies indicative of the enhancement which accompanies supernova-driven bubbles.

The results of this study were published as
Pidopryhora, Y., Lockman, F. J., & Shields J. C. ApJ 656, 928 (2007)

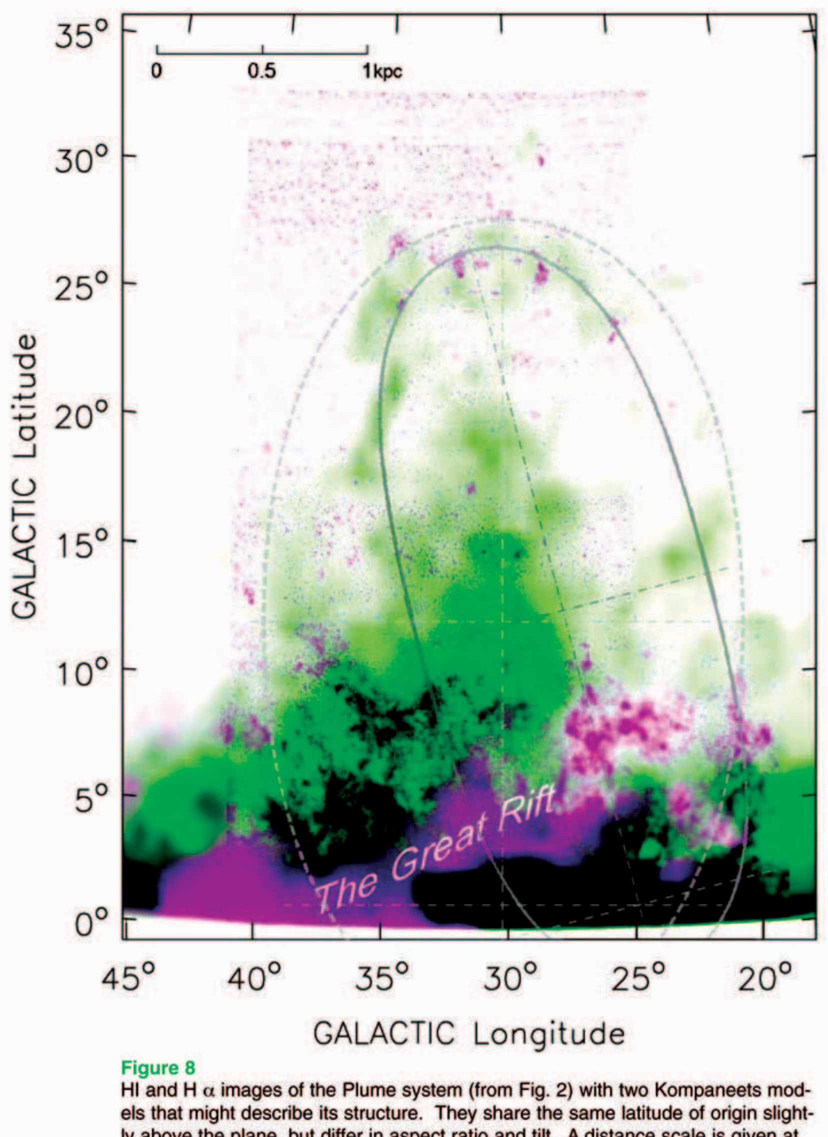

Figure 8
HI and H α images of the Plume system (from Fig. 2) with two Kompaneets models that might describe its structure. They share the same latitude of origin slightly above the plane, but differ in aspect ratio and tilt. A distance scale is given at the top of the Figure. The implied ages and energetics of the two models are quite similar however, and, because the system is so large, are reasonably robust to small changes in initial conditions. A tilt is expected from the change in gravitational potential over so large a system, and matches the general tilt of the HI whiskers.

Tables

Table 1. Kompaneets Model

Property	Distance factor[a]	Model 1	Model 2
Model parameters:			
Evolution factor, $y/2H$	-	0.999	0.980
Scale height H, kpc	d_7	0.23	0.42
Results:			
Age t, Myr, as a function of source luminosity L_0 (in $L_{\odot}$) and source density n_0 (in cm^{-3})	$d_7^{5/3}$	$680\ n_0^{1/3} L_0^{-1/3}$	$1760\ n_0^{1/3} L_0^{-1/3}$
$L_0 = 10^5 L_{\odot},\ n_0 = 1\ cm^{-3}$		15	38
Internal energy E_{th}, erg as a function of L_0 and n_0	$d_7^{5/3}$	$4 \times 10^{49}\ n_0^{1/3} L_0^{2/3}$	$10^{50}\ n_0^{1/3} L_0^{2/3}$
$L_0 = 10^5 L_{\odot},\ n_0 = 1\ cm^{-3}$		8×10^{52}	2×10^{53}

[a] We have adopted the kinematic disatnce of 7 kpc as a model distance to the Plume System. For a distance different from 7 kpc each table value should be multiplied by the corresponding power of d_7.

Table 2. The Properties of the Plume

Property	Distance factor	Unit	Value
Distance	d_7	kpc	7
Height above the Galactic plane	d_7	kpc	3.4
Size	d_7	kpc	1.2×0.6
H I Mass	d_7^2	$M_{\odot}$	3×10^4
Characteristic LSR velocity	-	km s^{-1}	70
Typical FWHM	-	km s^{-1}	15
Potential energy	d_7^3	erg	10^{52}
Ionization rate	d_7^2	photons s^{-1}	5×10^{50}

Table 3. The Properties of the Entire Plume System

Property	Distance factor	Unit	Value
Distance	d_7	kpc	7
Size	d_7	kpc	2.7×4.2
H I Mass	d_7^2	$M_{\odot}$	$\sim 10^6$
H^+ Mass	$d_7^{2.5}$	$M_{\odot}$	$1 - 3 \times 10^6$
Age	$d_7^{5/3}$	Myr	≈ 30
Thermal energy	$d_7^{5/3}$	erg	10^{53}

JOINT INSTITUTE FOR VLBI IN EUROPE

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.