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ONE PROBLEM

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THE COMPLETE SURVEY OF OUTFLOWS IN PERSEUS

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ABSTRACT

We present a study on the impact of molecular outflows in the Perseus molecular cloud complex using the COMPLETE Survey large-scale ^{12}CO(1–0) and ^{13}CO(1–0) maps. We used three-dimensional isosurface models generated in right ascension–declination–velocity space to visualize the maps. This rendering of the molecular line data allowed for a rapid and efficient way to search for molecular outflows over a large ($\sim$16 deg^2) area. Our outflow-searching technique detected previously known molecular outflows as well as new candidate outflows. Most of these new outflow-related high-velocity features lie in regions that have been poorly studied before. These new outflow candidates more than double the amount of outflow mass, momentum, and kinetic energy in the Perseus cloud complex. Our results indicate that outflows have significant impact on the environment immediately surrounding localized regions of active star formation, but lack the energy needed to feed the observed turbulence in the *entire* Perseus complex. This implies that other energy sources, in addition to protostellar outflows, are responsible for turbulence on a global cloud scale in Perseus. We studied the impact of outflows in six regions with active star formation within Perseus of sizes in the range of 1–4 pc. We find that outflows have enough power to maintain the turbulence in these regions and enough momentum to disperse and unbind some mass from them. We found no correlation between outflow strength and star formation efficiency (SFE) for the six different regions we studied, contrary to results of recent numerical simulations. The low fraction of gas that potentially could be ejected due to outflows suggests that additional mechanisms other than cloud dispersal by outflows are needed to explain low SFEs in clusters.

Key words: ISM: clouds – ISM: individual objects (Perseus) – ISM: jets and outflows – ISM: kinematics and dynamics – stars: formation – turbulence

Online-only material: color figures

2. DATA

In this paper, we use the ^{12}CO(1–0) and ^{13}CO(1–0) data collected for Perseus as part of the COordinated Molecular Probe Line Extinction Thermal Emission (COMPLETE) Survey of Star Forming Regions,[6] described in detail by Ridge et al. (2006b). The ^{12}CO and ^{13}CO molecular line maps were observed between 2002 and 2005 using the 14 m Five College Radio Astronomy Observatory (FCRAO) telescope with the SEQUOIA 32-element focal plane array. The receiver was used with a digital correlator providing a total bandwidth of 25 MHz over 1024 channels. The ^{12}CO $J = 1$–0 (115.271 GHz) and the ^{13}CO $J = 1$–0 (110.201 GHz) transitions were observed simultaneously using an on-the-fly (OTF) mapping technique. The beam telescope at these frequencies is about 46″. Both maps of ^{12}CO and ^{13}CO are essential for a thorough study of the outflow and cloud properties. The ^{12}CO(1–0) is a good tracer of the cool and massive molecular outflows and provides the information needed to study the impact of these energetic phenomena on the cloud. The ^{13}CO(1–0) provides an estimate of the optical depth of the ^{12}CO(1–0) line and can be used to probe the cloud structure and kinematics.

Observations were made in $10' \times 10'$ maps with an effective velocity resolution of 0.07 km s^{-1}. These small maps were then patched together to form the final large map of Perseus, which is about $6.^\circ 25 \times 3^\circ$. Calibration was done via the chopper-wheel technique (Kutner & Ulich 1981), yielding spectra with units of T_A^*. We removed noisy pixels that were more than 3 times the average rms noise of the data cube, the entire map was then resampled to a 46″ grid, and the spectral axis was Hanning smoothed[7] (necessary to keep the cubes to a size manageable by

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We divided the Perseus cloud into six areas (with similar cloud central LSR velocities) for easier visualization and outflow search in 3D Slicer (see below). The borders of these areas are similar to those named by Pineda et al. (2008), who also based their division mainly on the cloud's central LSR velocity. The regions, whose outlines are shown in Figure 1, overlap between 1 and 3 arcmin to guarantee complete analysis. This overlap was checked to be sufficient based on the fact that new and known outflows which crossed regions were successfully double-identified.

For each area, an isosurface (constant intensity level) model was generated in 3D Slicer, using the ^{12}CO(1–0) map. The threshold emission intensity level chosen for each isosurface model was the lowest level of emission above the rms noise level for that particular region. This creates a three-dimensional model representing all of the detected emission. The high-velocity gas in this three-dimensional space can be identified in the form of spikes, as shown for the B5 region in Figure 2, which visually stick out from the general distribution of the gas. These sharp protrusions occur since one is looking at the radial velocity component of the gas along the line of sight, thus causing spikes wherever there is gas at distinct velocities far away from the main cloud velocity. Instead of having to go through each region and carefully examine each channel map, or randomly scroll through the spectra by hand, this visualization allows one to instantly see where the high-velocity points are located (see also Borkin et al. 2007, 2008).

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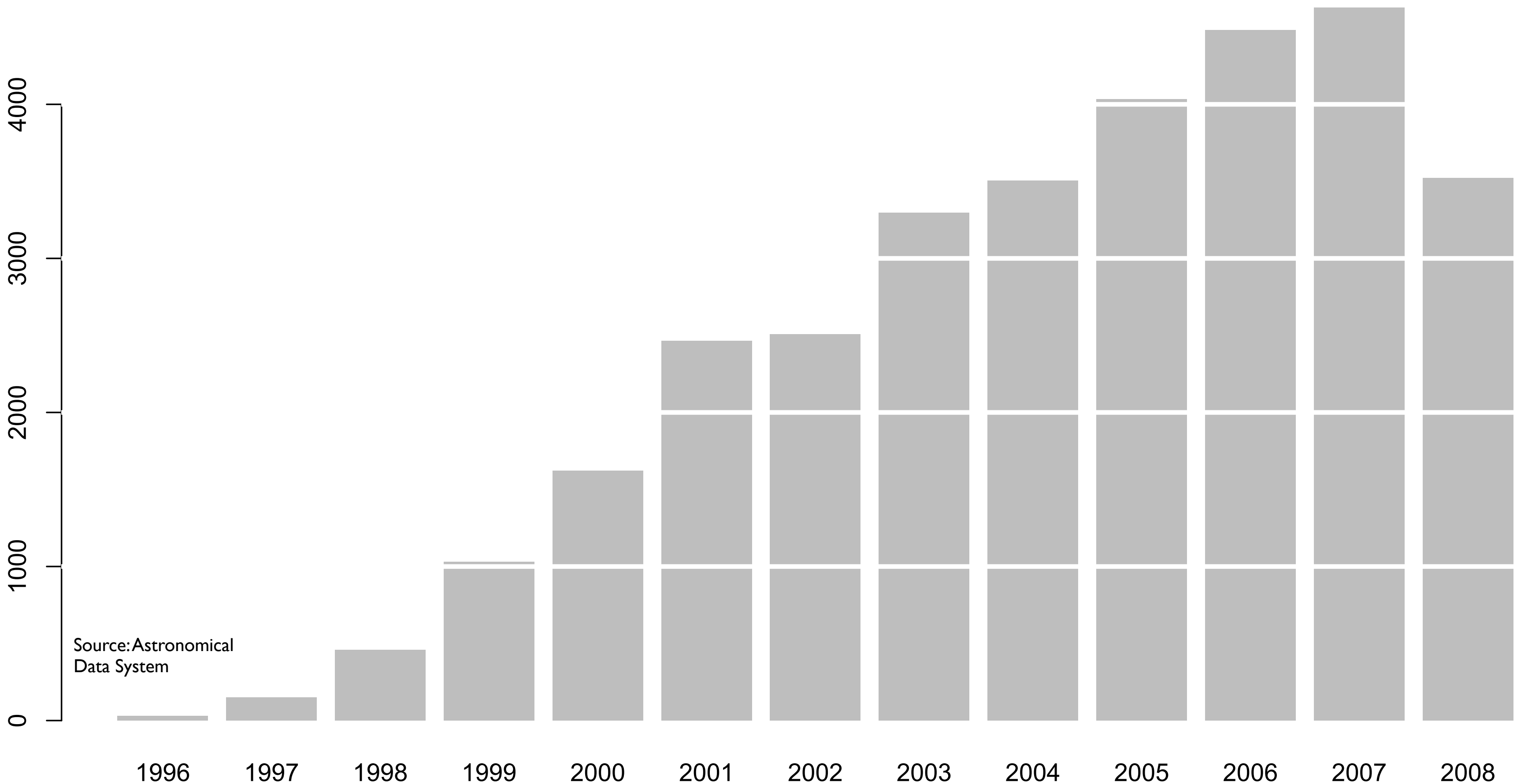

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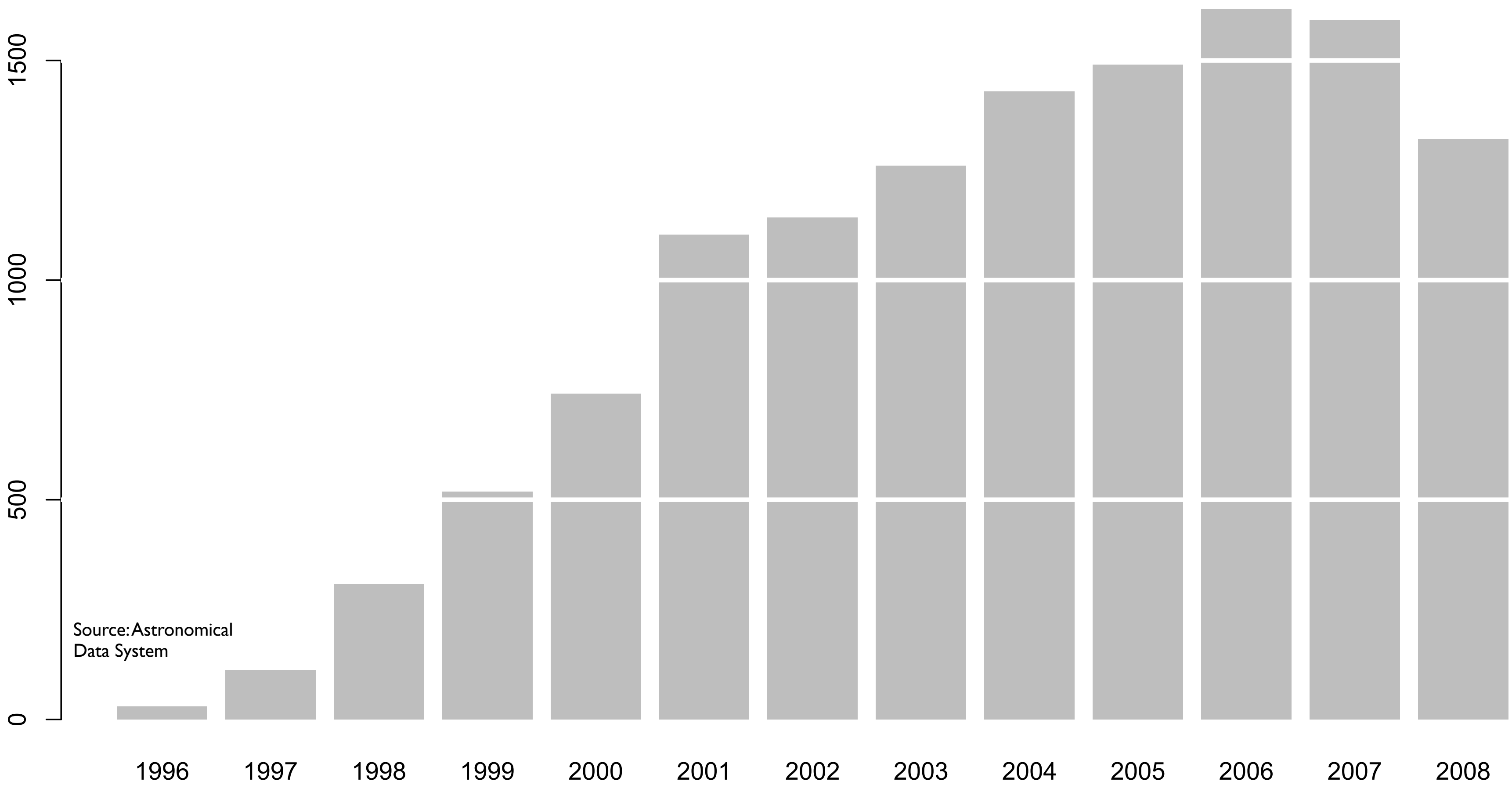

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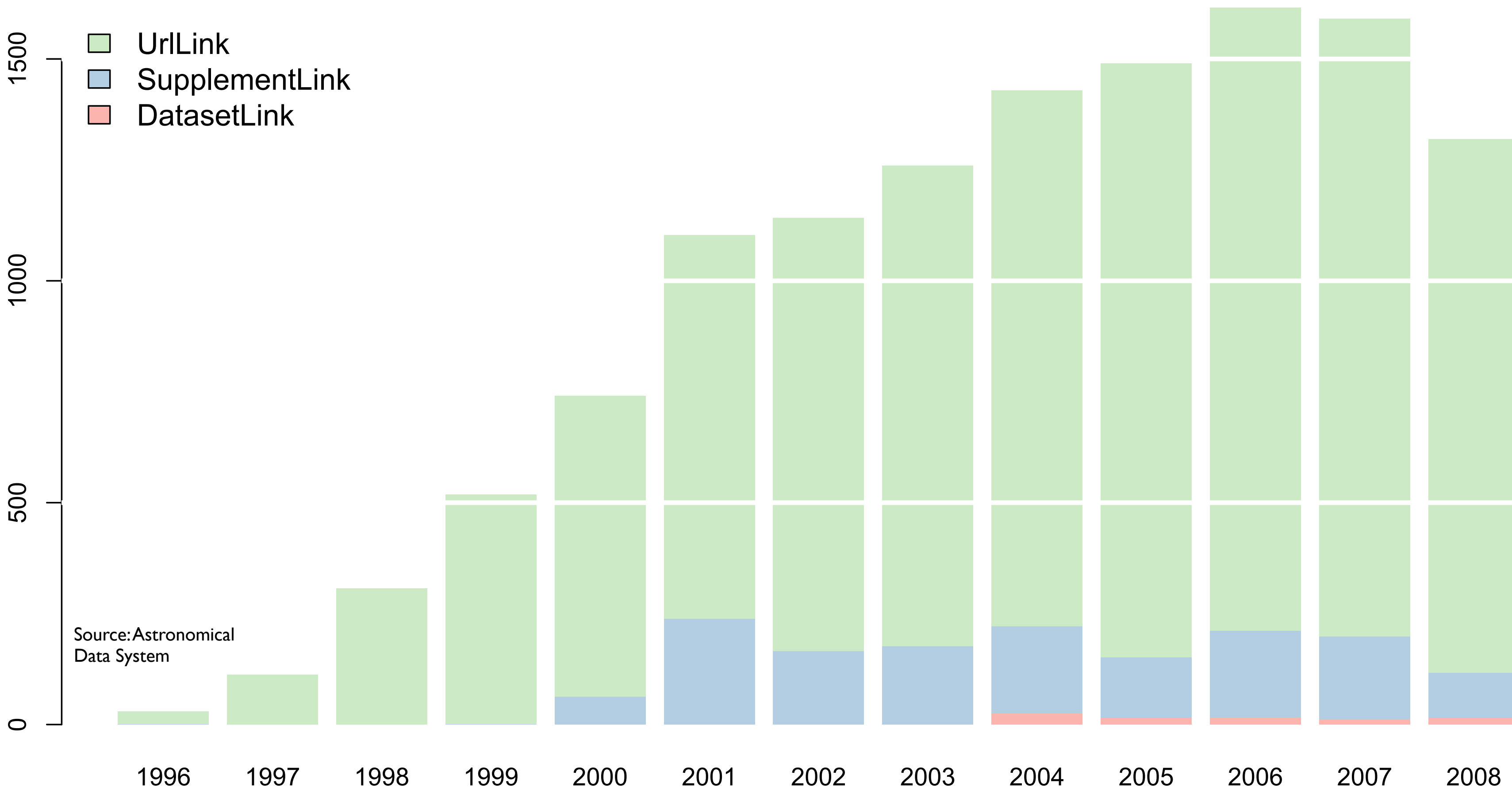

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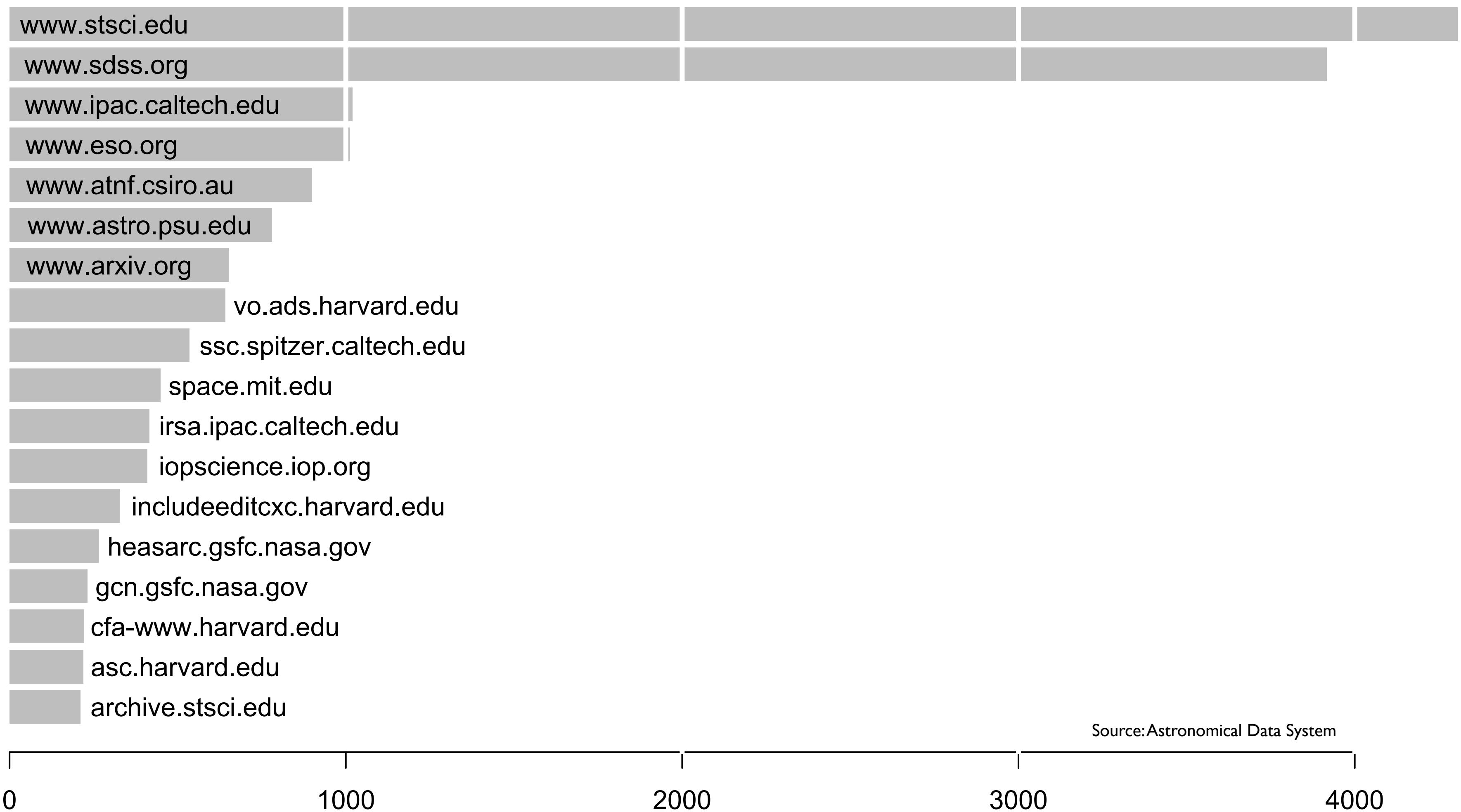

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2. DATA

In this paper, we use the ^{12}CO(1–0) and ^{13}CO(1–0) data collected for Perseus as part of the COordinated Molecular Probe Line Extinction Thermal Emission (COMPLETE) Survey of Star Forming Regions,[6] described in detail by Ridge et al. (2006b). The ^{12}CO and ^{13}CO molecular line maps were observed between 2002 and 2005 using the 14 m Five College Radio Astronomy Observatory (FCRAO) telescope with the SEQUOIA 32-element focal plane array. The receiver was used with a digital correlator providing a total bandwidth of 25 MHz over 1024 channels. The ^{12}CO $J = 1$–0 (115.271 GHz) and the ^{13}CO $J = 1$–0 (110.201 GHz) transitions were observed simultaneously using an on-the-fly (OTF) mapping technique. The beam telescope at these frequencies is about 46″. Both maps of ^{12}CO and ^{13}CO are essential for a thorough study of the outflow and cloud properties. The ^{12}CO(1–0) is a good tracer of the cool and massive molecular outflows and provides the information needed to study the impact of these energetic phenomena on the cloud. The ^{13}CO(1–0) provides an estimate of the optical depth of the ^{12}CO(1–0) line and can be used to probe the cloud structure and kinematics.

Observations were made in $10' \times 10'$ maps with an effective velocity resolution of 0.07 km s^{-1}. These small maps were then patched together to form the final large map of Perseus, which is about $6.^{\circ}25 \times 3^{\circ}$. Calibration was done via the chopper-wheel technique (Kutner & Ulich 1981), yielding spectra with units of T_A^*. We removed noisy pixels that were more than 3 times the average rms noise of the data cube, the entire map was then resampled to a 46″ grid, and the spectral axis was Hanning smoothed[7] (necessary to keep the cubes to a size manageable by hierarchical structure of star-forming cores and velocity structure of IC 348 with ^{13}CO(1–0) and C^{18}O(1–0) data.

We divided the Perseus cloud into six areas (with similar cloud central LSR velocities) for easier visualization and outflow search in 3D Slicer (see below). The borders of these areas are similar to those named by Pineda et al. (2008), who also based their division mainly on the cloud's central LSR velocity. The regions, whose outlines are shown in Figure 1, overlap between 1 and 3 arcmin to guarantee complete analysis. This overlap was checked to be sufficient based on the fact that new and known outflows which crossed regions were successfully double-identified.

For each area, an isosurface (constant intensity level) model was generated in 3D Slicer, using the ^{12}CO(1–0) map. The threshold emission intensity level chosen for each isosurface model was the lowest level of emission above the rms noise level for that particular region. This creates a three-dimensional model representing all of the detected emission. The high-velocity gas in this three-dimensional space can be identified in the form of spikes, as shown for the B5 region in Figure 2, which visually stick out from the general distribution of the gas. These sharp protrusions occur since one is looking at the radial velocity component of the gas along the line of sight, thus causing spikes wherever there is gas at distinct velocities far away from the main cloud velocity. Instead of having to go through each region and carefully examine each channel map, or randomly scroll through the spectra by hand, this visualization allows one to instantly see where the high-velocity points are located (see also Borkin et al. 2007, 2008).

6 See http://www.cfa.harvard.edu/COMPLETE.
7 See http://www.cfa.harvard.edu/COMPLETE/projects/outflows.html for a link to the molecular line maps.

8 This work is done as part of the Astronomical Medicine project (http://am.iic.harvard.edu) at the Initiative in Innovative Computing at Harvard (http://iic.harvard.edu). The goal of the project is to address common research challenges to both the fields of medical imaging and astronomy including visualization, image analysis, and accessibility of large varying kinds of data.
9 http://www.slicer.org/

COMPLETE

The COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions

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Project Description

The COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions (COMPLETE) provides a range of data complementary to the Spitzer Legacy Program "From Molecular Cores to Planet Forming Disks" (c2d) for the Perseus, Ophiuchus and Serpens regions. In combination with the Spitzer observations, COMPLETE will allow for detailed analysis and understanding of the physics of star formation on scales from 500 A.U. to 10 pc.

Phase I, which is now complete, provides fully sampled, arcminute resolution observations of the density and velocity structure of the three regions, comprising: extinction maps derived from the Two Micron All Sky Survey (2MASS) near-infrared data using the NICER algorithm; extinction and temperature maps derived from IRAS 60 and 100um emission; HI maps of atomic gas; 12CO and 13CO maps of molecular gas; and submillimeter continuum images of emission from dust in dense cores.

Click on the "Data" button to the left to access this data.

Phase II (which is still ongoing) uses targeted source lists based on the Phase I data, as it is (still) not feasible to cover every dense star-forming peak at high resolution. Phase II includes high-sensitivity near-IR imaging (for high resolution extinction mapping), mm-continuum imaging with MAMBO on IRAM and high-resolution observations of dense gas tracers such as N2H+. These data are being released as they are validated.

COMPLETE Movies: Check-out our movies page for animations of the COMPLETE data cubes in 3D.

Referencing Data from the COMPLETE Survey

COMPLETE data are non-proprietary. Please reference **Ridge, N.A. et al., *"The COMPLETE Survey of Star Forming Regions: Phase 1 Data"*, 2006, AJ, 131, 2921** as the data source. However, we would like to keep a record of work that is using COMPLETE data, so please send us an email (with a reference if possible) if you make use of any data provided here.

Recent COMPLETE Publications

NEW Helen Kirk, Jaime E. Pineda, Doug Johnstone, and Alyssa A. Goodman, 2010, *The Dynamics of Dense Cores in the Perseus Molecular Cloud II: The Relationship Between Dense Cores and the Cloud*, Accepted to ApJ. (astro-ph | ADS)

UPDATED Héctor G. Arce, Michelle Borkin, Alyssa A. Goodman, Jaime E. Pineda, Michael Halle, 2010, *The COMPLETE Survey of Outflows in Perseus*, ApJ, 715, 117. (Local | Project webpage | astro-ph | ADS)

UPDATED Jaime E. Pineda, Alyssa A. Goodman, Héctor G. Arce, Paola Caselli, Jonathan B. Foster, Philip C. Myers, Erik W. Rosolowsky, 2010, *Direct observation of a sharp transition to coherence in Dense Cores*, ApJL, 712, 116. (Local | astro-ph | ADS)

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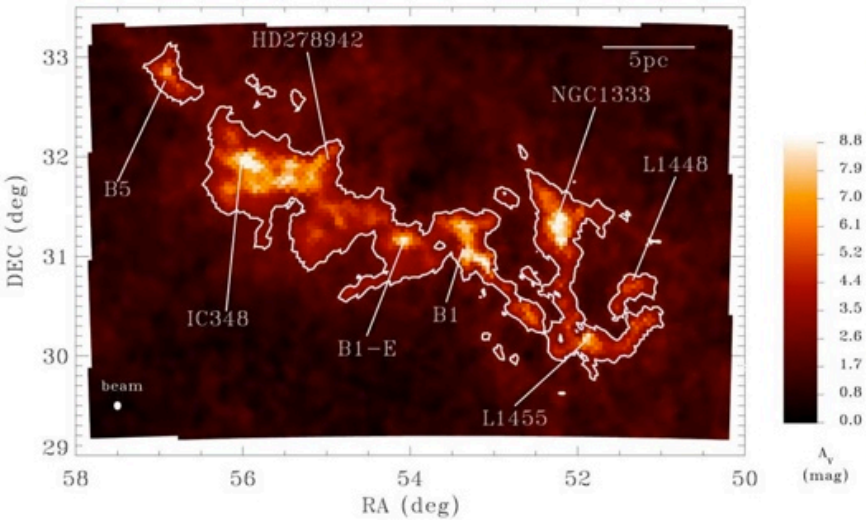
COMPLETE

2MASS/NICER Perseus Extinction Data

Back to 2MASS Data Page



Description:

Extinciton maps made from 2MASS and NICER (Near Infrared Extinction-method Revisited). This map is made from the final 2MASS data release and cover all of Perseus. The data values are magnitudes of visual extinction (Av). Consult the error map and stellar density map to identify any problematic regions (few in this map). Versions in galactic and equatorial coordinates are provided. The equatorial versions look less smooth, since they were regridded without re-orientating pixels. FITS headers for all these files occasionally refuse to play nicely with certain programs, but all display correctly in something like DS9.

Contact Person:

Jonathan Foster, Harvard-Smithsonian Center for Astrophysics

Telescope:

2MASS

Status:

Finished

Sampling:

N/A

Areal Coverage:

9 by 12 degrees

Map Center (Galactic):

l = 159.90
b = -20.73

Map Center (J2000):

RA = 03:33:55
Dec = 30:14:27

Downloads:

- PerA_Extn2MASS_F_Gal.fits Map in Galactic Coordinates (436 K)
- PerA_Extn2MASS_F_Err-Gal.fits Error map in Galactic Coordinates (436 K)
- PerA_Extn2MASS_F_Den-Gal.fits Stellar density map in Galactic Coordinates (436 K)
- PerA_Extn2MASS_F_Eq.fits Map in Equatorial Coordinates (984 K)
- PerA_Extn2MASS_F_Err-Eq.fits Error map in Equatorial Coordinates (984 K)
- PerA_Extn2MASS_F_Den-Eq.fits Stellar density map in Equatorial Coordinates (984 K)
- Info File (All comments and information about this data)

Comments on Resolution:

The map is smoothed with a gaussian filter with FWHM = 5 arcminutes or two pixels, so each pixel is 2.5 arcminutes.

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Title:	The COMPLETE Survey of Outflows in Perseus
Authors:	Arce, Héctor G.; Borkin, Michelle A.; Goodman, Alyssa A.; Pineda, Jaime E.; Halle, Michael W.
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Publication:	The Astrophysical Journal, Volume 715, Issue 2, pp. 1170-1190 (2010). (ApJ Homepage)
Publication Date:	06/2010
Origin:	IOP
ApJ Keywords:	ISM: clouds, ISM: individual objects: Perseus, ISM: jets and outflows, ISM: kinematics and dynamics, stars: formation, turbulence
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DATA?

Title:	The COM ETE Survey o utflow n P us
Authors:	Arce, Héc G.; Borkin, M elle A.; Goodm , Alyssa A.; Pineda, Jai E.; H , Michael .
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Bibliographic Code:	2010ApJ...715.1170A

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citation

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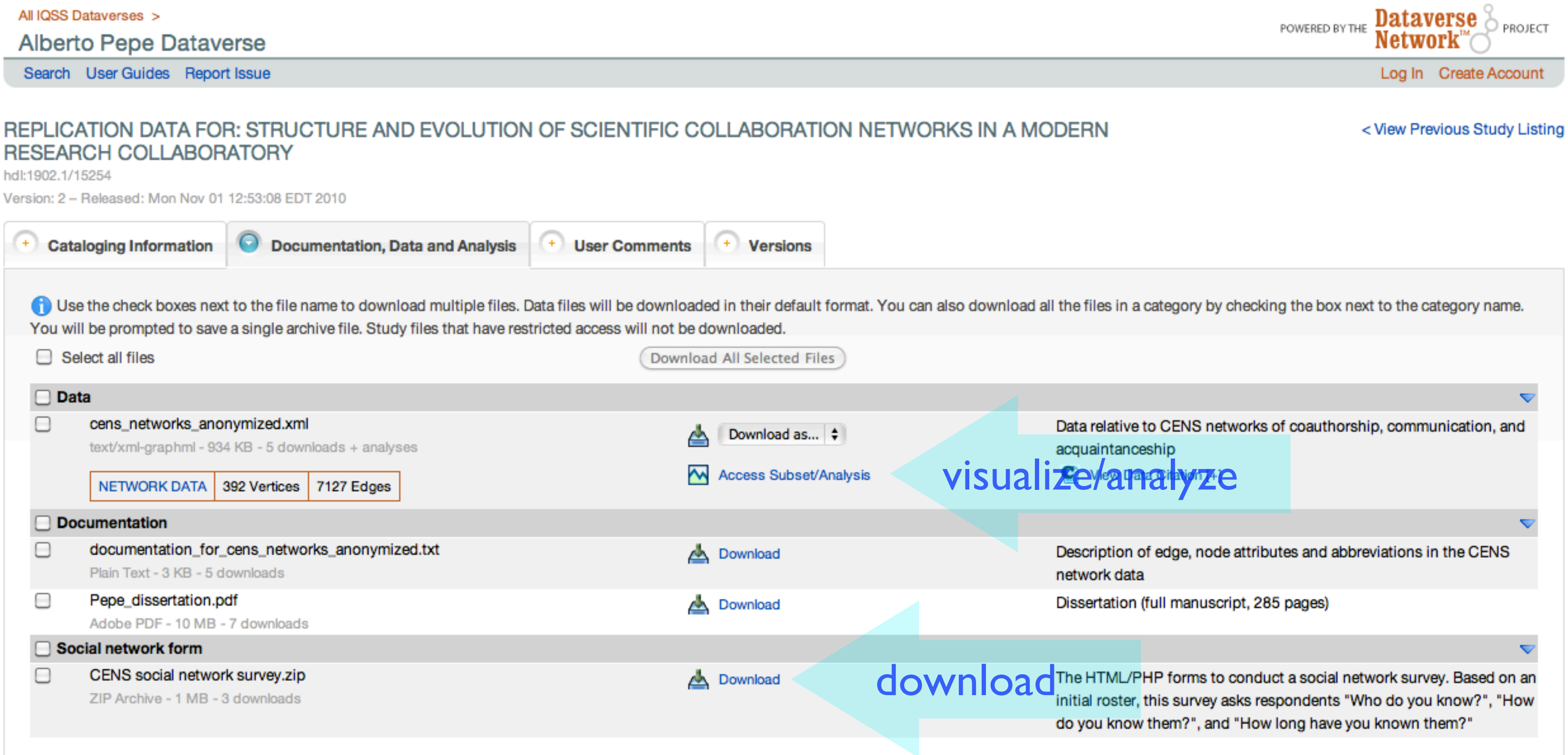

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THANK YOU

The work presented here was performed in collaboration with **Alyssa Goodman** (Harvard), **Michael Kurtz** (Harvard-Smithsonian), **August Muench** (Harvard-Smithsonian), **Jay Luker** (Harvard-Smithsonian), **Christopher Erdmann** (CfA Library), **Alberto Accomazzi** (ADS), **Giovanni Di Milia** (ADS), **Merce Crosas** (IQSS)