

# The Future of Astronomy



**Alyssa A. Goodman**

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*WGBH Scholar-in-Residence*

# 3500 years of Observing

Stonehenge, 1500 BC



Ptolemy in Alexandria, 100 AD



Observatory Tower, Lincolnshire, UK, c. 1300



Galileo, 1600



The "Scientific Revolution"

Reber's Radio Telescope, 1937



NASA/Explorer 7  
(Space-based  
Observing)  
1959

"The Internet"

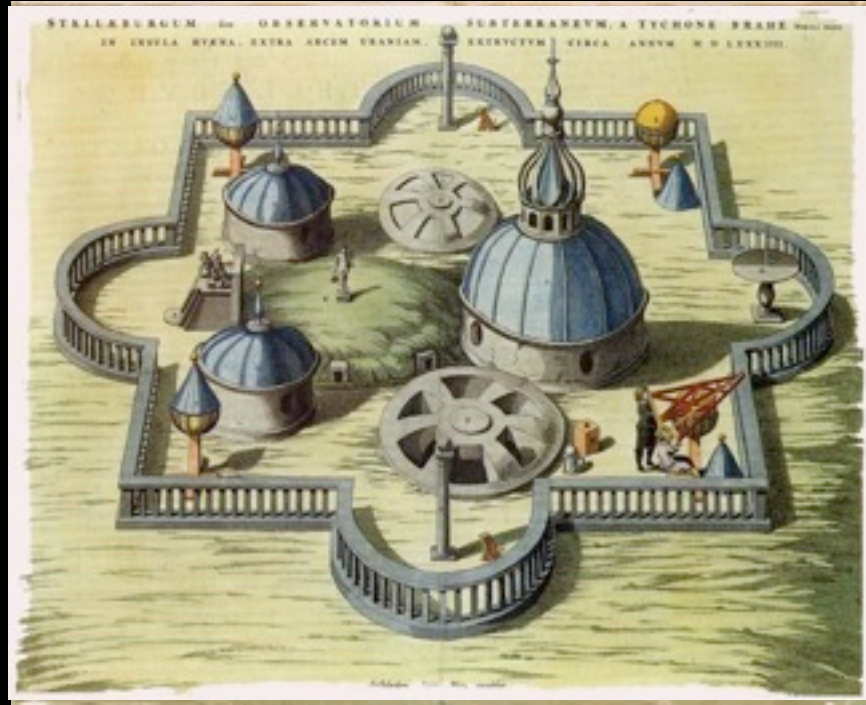


Long-distance  
remote-control/  
"robotic"  
telescopes  
1990s



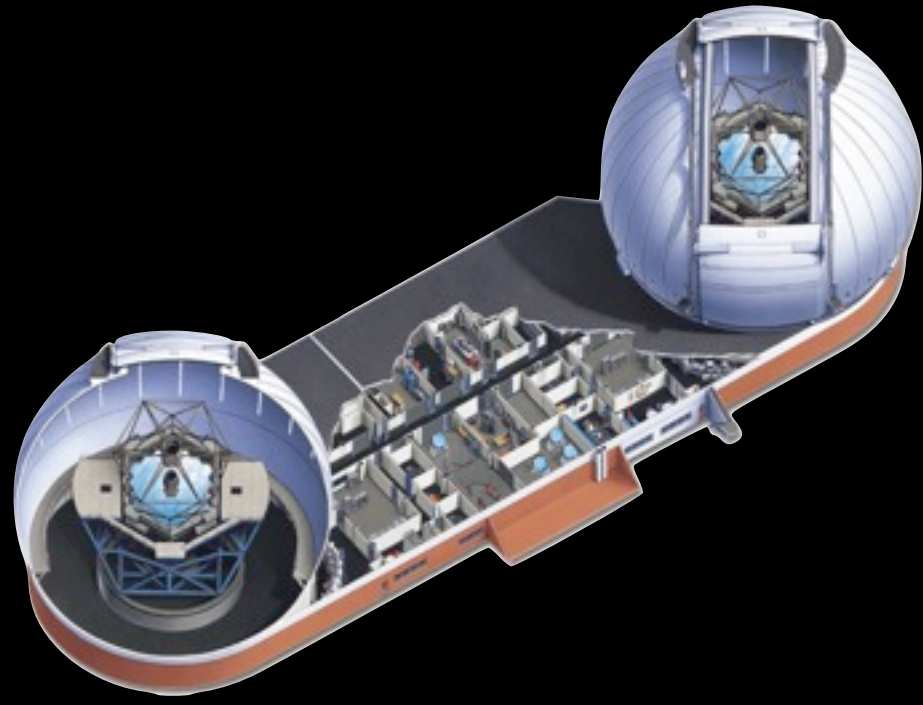
"Virtual  
Observatories"  
21st century

# Stjerneborg (Tycho Brahe, 1586)



Galileo: c. 1609

# W.H. Keck Observatory (1995+)

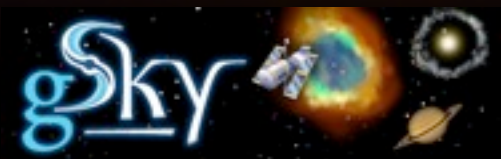
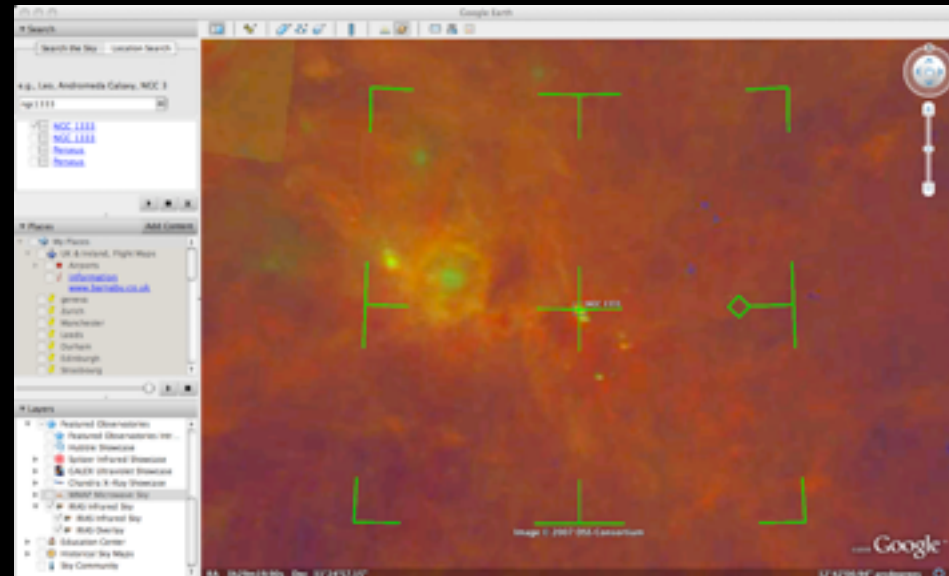


Full-sky virtual astronomy:  
c. 2023?

# “One Earth, One Sky”

Microsoft

Google



# WWT 2001

VIEWPOINT

## The World-Wide Telescope

Alexander Szalav,<sup>1</sup> Iim Grav<sup>2</sup>

1, 2007

All astronomy data and literature will soon be online and accessible via the Internet. The community is building the Virtual Observatory, an organization of this worldwide data into a coherent whole that can be accessed by anyone, in any form, from anywhere. The resulting system will dramatically improve our ability to do multi-spectral and temporal studies that integrate data from multiple instruments. The Virtual Observatory data also provide a wonderful base for teaching astronomy, scientific discovery, and computational science.

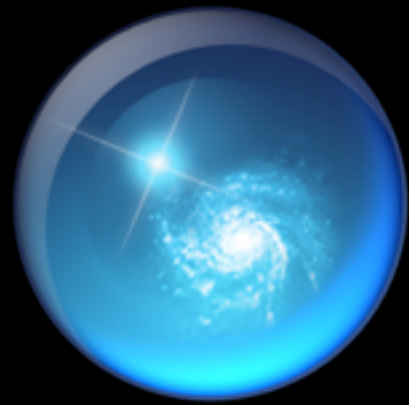
Hubble Space Telescope (HST) (1), the Chandra X-Ray Observatory (2), the Sloan Digital Sky Survey (SDSS) (3), the Two Mi-

spectral surveys. Together, they house an order of magnitude more data than any single instrument. In addition, all the astronomy literature is online and is cross-indexed with the observations (6, 7).

Why is it necessary to study the sky in such detail? Celestial objects radiate energy over an

Fig. 1. Telescope area doubles every 25 years, whereas telescope CCD pixels double every 2 years. This rate seems to be accelerating. It implies a yearly data doubling. Huge advances in storage, computing, and communications technologies have enabled the Internet and will enable the Virtual Observatory.

# WWT Today



quick demo of WWT

# “WWT as a Preview of 21st Century *e-Research* in Astronomy”

(based on American Astronomical Society Meeting presentation, Long Beach, CA, 2009)

–OR–

Group chose this one, so I've added these slides next...

“Astronomical Data and Information *Visualization*”

(based on American Astronomical Society Meeting , Washington, DC, 2010)





# Astronomical Data and Information Visualization

Alyssa A. Goodman

*Harvard-Smithsonian Center for Astrophysics  
Initiative in Innovative Computing at Harvard  
WGBH Scholar-in-Residence*





# Relative Strengths

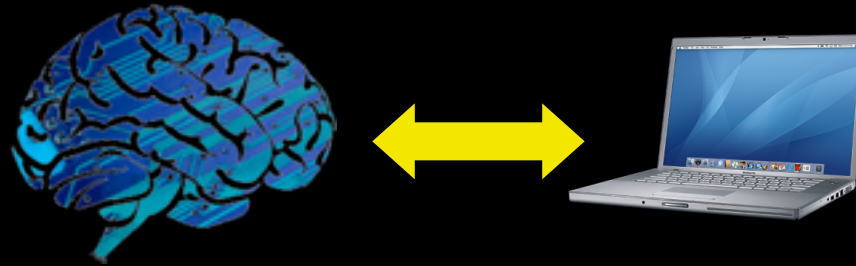


Pattern Recognition  
Creativity



Calculations





Data Reduction

Data Display

Context (e.g. journals + online data)

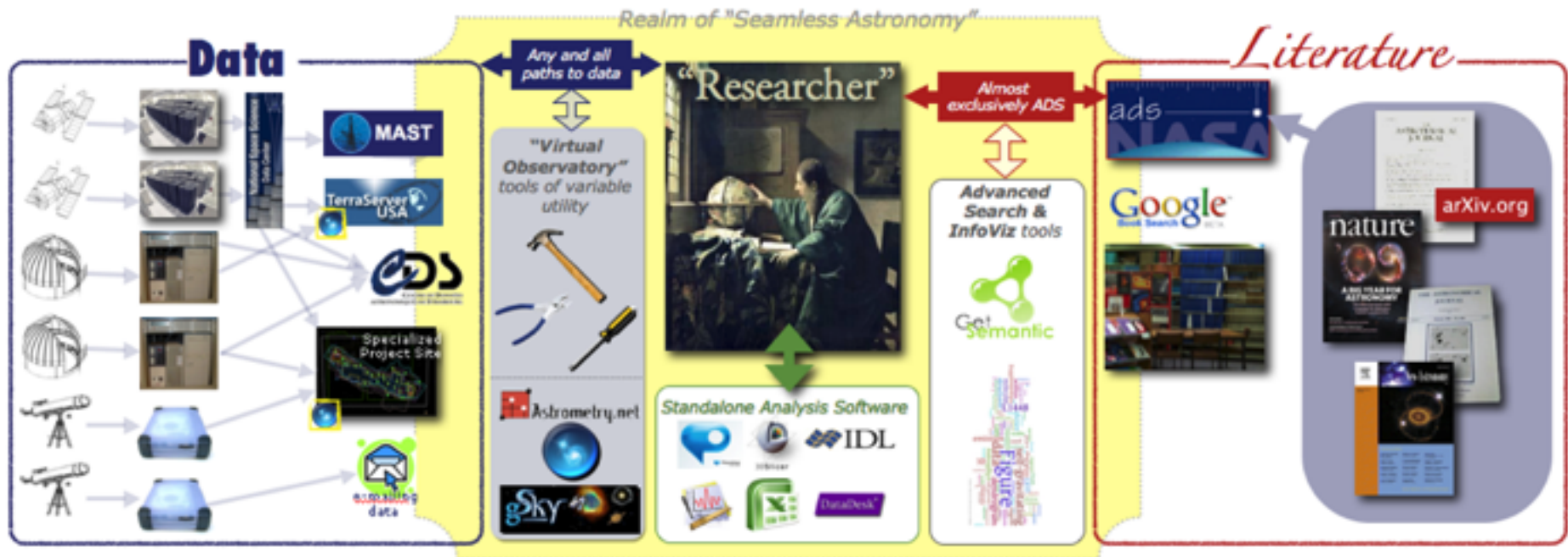
Simulation Design

Statistics Design

Data Exploration (Visualization)

# Seamless Astronomy

[www.cfa.harvard.edu/~agoodman](http://www.cfa.harvard.edu/~agoodman) and [worldwidetelescope.org](http://worldwidetelescope.org)



*“Seamless Astronomy” is collaboration amongst many researchers at CfA, MSR, Princeton, STScI, NYU, RPI, and UCLA, and it is supported by NASA, NSF and Microsoft External Research.*

# Seamless Astronomy

The interface is titled "AstroNavigator" and features a navigation bar with "Project 1", "Project 2", "Project 3", and "Edit" buttons. The main content area is divided into several panels:

- Top Left:** A search results panel for "QSO MgII absorption line observed". It lists authors "Drinkwater" and "Webster R.L., T..." and includes a large letter "A" and a description: "The results of a large R-band".
- Top Center:** A "Literature Viewer" window displaying a scientific paper with text and several small plots.
- Top Right:** A plot titled "Self-gravitating Structures" showing the "Fraction of Emission in Self-gravitating Structures" on the y-axis (log scale from 0.01 to 1.00) versus "Scale (pc)" on the x-axis (log scale from 0.1 to 1.0). It compares "L1448" (black line with circles) and "Simulation" (grey line with squares).
- Bottom Left:** A "Data Viewer" window showing a large, detailed image of a galaxy or nebula, with a smaller thumbnail strip above it.
- Bottom Right:** An "Ar3Dive Browser" window showing a 3D visualization of a galaxy or nebula, with text "IC 348 Example Required" and "results 1-20 of 907".

**Semantic Search**

**Literature Viewer**

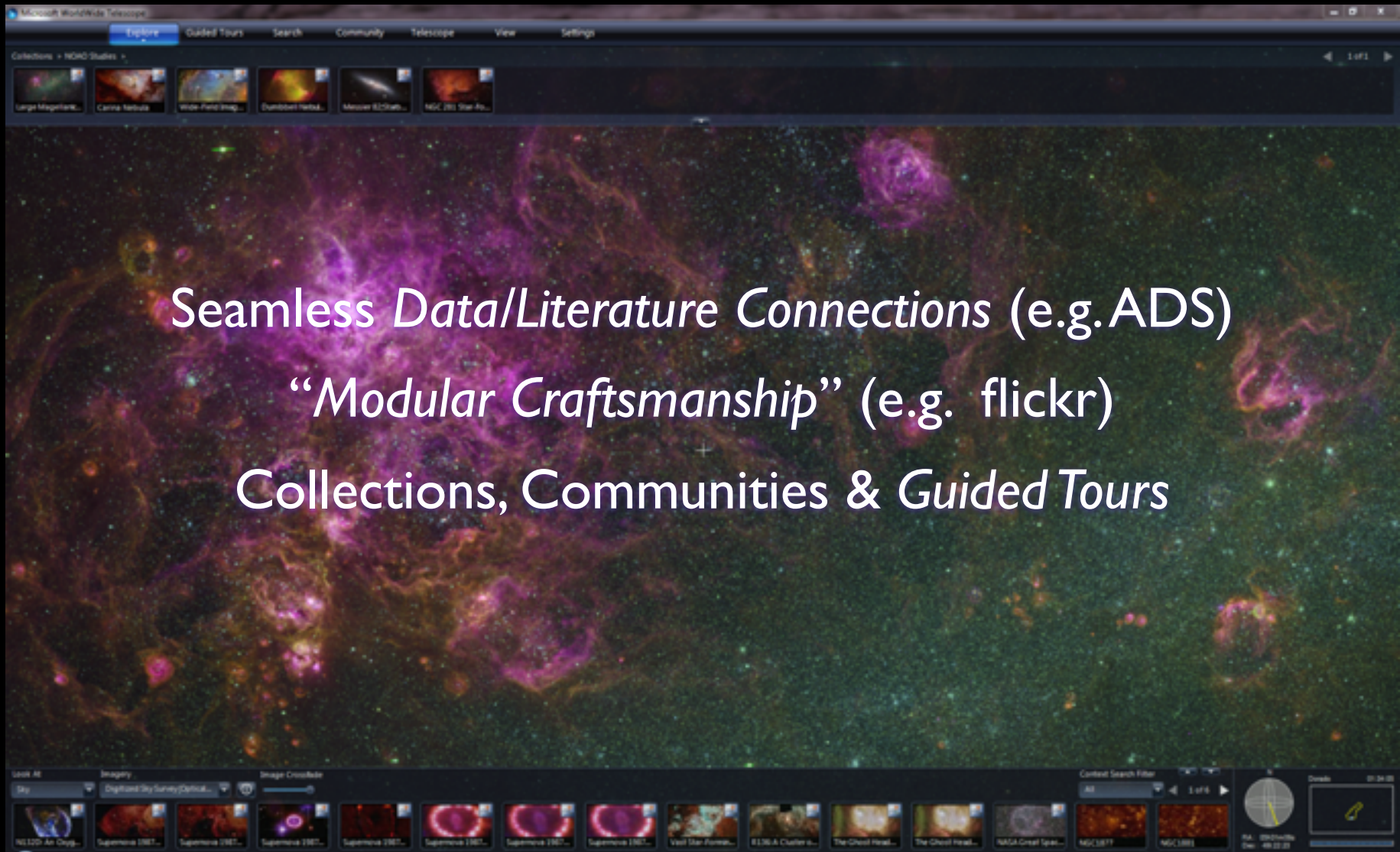
**Info-Bias for Analytics Results**

**Data Viewer (e.g. WWT)**

**Ar3Dive Browser**

Mockup based on work of Eli Bressert, excerpted from NASA AISRP proposal by Goodman, Muench, Christian, Conti, Kurtz, Burke, Accomazzi, McGuinness, Hendler & Wong, 2008

# “WorldWide Telescope”: a UIS from Microsoft Research [UIS=Universe Information System]



Created by Curtis Wong and Jonathan Fay at MSR; AG is “Academic Partner” on the WWT Project

Explore

Guided Tours

Search

View

Settings

ngc 7023

Plot Results

VO Search

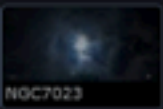
J2000

RA

Dec

Go

1 of 2



NGC7023



**Finder Scope**



Classification:  
Reflection Nebula  
in Cepheus

**NGC 7023**

RA:	21h01m36s	Magnitude:	n/a
Dec:	68 : 10 : 11	Distance:	n/a
Alt:	30 : 55 : 38	Rise:	Circumpolar
Az:	341 : 36 : 56	Transit:	Circumpolar
	Set:		Circumpolar

Image Credits:  
Jack Newton

<http://www.jacknewton.com/>




Research Show Object Close

Look At: Sky Imagery: Digitized Sky Survey (Opt)

1 of 23

Cepheus 00:14:04

RA : 21h01m36s



ngc 7023

Plot Results VO Search J2000 RA Dec Go

1 of 2



**Finder Scope**



Classification:  
Reflection Nebula  
in Cepheus

**NGC 7023**

RA: 21h01m36s Magnitude: n/a  
Dec: 68 : 10 : 11 Distance: n/a  
Alt: 30 : 53 : 38 Rise: Circumpolar

Name: NGC 7023

Information ▶  
Imagery ▶  
Virtual Observatory Searches ▶  
Set as Foreground Imagery  
Set as Background Imagery Close

Properties  
Copy Shortcut

- Look up on SIMBAD
- Look up on SEDS
- Look up on Wikipedia
- Look up publications on ADS**
- Look up on NED
- Look up on SDSS



Look At Imagery

Digitized Sky Survey (Optical)

Sculptor Earth Uranus

1 of 23

Cepheus 00:1

RA : 21h01m36s  
Dec : 68:10:11

Sculptor Galaxy Cartwheel Galaxy Cartwheel Galaxy

[SAO/NASA Astrophysics Data System \(ADS\)](#)
**Query Results from the Astronomy Database**
[Go to bottom of page](#)

 Retrieved **200** abstracts, starting with number **1**. Total number selected: **393**.

 Sort options 

#	Bibcode Authors	Score	Date	List of Links Access Control Help			
1	<a href="#">2009ApJ...700.1609M</a> Myers, Philip C.	1.000	08/2009	<a href="#">A</a> <a href="#">Z</a> <a href="#">E</a> <a href="#">E</a> <a href="#">L</a> <a href="#">X</a>	<a href="#">R</a> <a href="#">C</a> <a href="#">S</a>	<a href="#">U</a>	
	Filamentary Structure of Star-forming Complexes						
2	<a href="#">2009ApJ...700.1190D</a> Desai, Vandana; Soifer, B. T.; Dey, Arjun; LeFlo'ch, Emeric; Armus, Lee; Brand, Kate; Brown, Michael J. I.; Brodwin, Mark; Jannuzi, Buell T.; Houck, James R.; and 8 coauthors	1.000	08/2009	<a href="#">A</a> <a href="#">Z</a> <a href="#">E</a> <a href="#">E</a> <a href="#">L</a> <a href="#">X</a>	<a href="#">R</a> <a href="#">C</a> <a href="#">S</a>	<a href="#">U</a>	
	Strong Polycyclic Aromatic Hydrocarbon Emission from z = 2 ULIRGs						
3	<a href="#">2009MNRAS.396.1851N</a> Nutter, D.; Stamatellos, D.; Wand- Thompson, D.	1.000	07/2009	<a href="#">A</a> <a href="#">Z</a> <a href="#">E</a> <a href="#">E</a> <a href="#">L</a> <a href="#">X</a>	<a href="#">R</a> <a href="#">S</a>	<a href="#">U</a>	
	The initial conditions of isolated star formation - IX. Akari mapping of an externally heated pre-stellar core						
4	<a href="#">2009A&amp;A...502..175B</a> Boersma, C.; Peeters, E.; Martín- Hernández, N. L.; van der Wolk, G.; Verhoeff, A. P.; Tielens, A. G. G. M.; Waters, L. B. F. M.; Pel, J. W.	1.000	07/2009	<a href="#">A</a> <a href="#">Z</a> <a href="#">E</a> <a href="#">E</a> <a href="#">L</a>	<a href="#">R</a> <a href="#">S</a>	<a href="#">U</a>	
	A spatial study of the mid-IR emission features in four Herbig Ae/Be stars						
5	<a href="#">2009MNRAS.395.1695H</a> Hernán-Caballero, A.; Pérez-Fourmon, I.; Hatziminaoglou, E.; Afonso-Luis, A.; Rowan-Robinson, M.; Rigopoulou, D.; Farrah, D.; Lonsdale, C. J.; Babbidge, T.;	1.000	05/2009	<a href="#">A</a> <a href="#">Z</a> <a href="#">E</a> <a href="#">E</a> <a href="#">L</a> <a href="#">X</a>	<a href="#">R</a> <a href="#">C</a> <a href="#">S</a>	<a href="#">U</a>	
	Mid-infrared spectroscopy of infrared-luminous galaxies at z ~ 0.5-3						



**Finder Scope**



Classification:  
Reflection Nebula  
in Cepheus

**NGC 7023**

RA: 21h01m36s Magnitude: n/a  
Dec: 68 : 10 : 11 Distance: n/a  
Alt: 30 : 53 : 38 Rise: Circumpolar

Name: NGC 7023

Information

Imagery

Virtual Observatory Searches

Set as Foreground Imagery

Set as Background Imagery

Properties

Copy Shortcut

- Look up on SIMBAD
- Look up on SEDS
- Look up on Wikipedia
- Look up publications on ADS
- Look up on NED
- Look up on SDSS



Look At Imagery

Digitized Sky Survey (Opt)

Sculptor Earth Uranus

1 of 23

Cepheus 00:1

RA : 21h01m36s  
Dec : 68:10:11

Sculptor Galaxy Cartwheel Galaxy Cartwheel Galaxy

SIMBAD query result

http://simbad.u-strasbg.fr/simbad/sim-id?ident=NGC+7023&sessionid=88f7cd92574727ffc

DCDCLXV Testify newKodak EXPLO Bing Clarke WWTSL Alyssa Good... Home Page Toofledo Harvard IIC: Projects Wikis Etc. Google Calendar \$\$\$ Image Search

DS SIMBAD VizieR Aladin Catalogs Dictionary Biblio Tutorials Developers

**SIMBAD query result**

other query modes: [Identifier query](#) [Coordinate query](#) [Criteria query](#) [Bibliography query](#) [Basic query](#) [Script submission](#) [Output options](#) [Help](#)

Object query : NGC 7023 C.D.S. - SIMBAD4 ref 1.132 - 2009.10.23CEST21:59:31

[Available data](#) [Basic data](#) [Identifiers](#) [Plot & images](#) [Bibliography](#) [Measurements](#) [External archives](#) [Notes](#)

**Basic data :**  
**NGC 7023 -- Open (galactic) Cluster**  with radius  arcmin

Other object types: [Cl\\*](#) (C, Cl, [R002003]) [OpC](#) (OCISM) [R12](#) (LRN) [V\\*](#) (AAVSO) [IR](#) (IRAS)

ICRS coord. (ep=2000): [21 01 34.9 +68 09 48 \(-\) \[ - - - \] D -](#)

FKS coord. (ep=2000 eq=2000): [21 01 34.9 +68 09 48 \(-\) \[ - - - \] D -](#)  
[104.0616 +14.1926 \(-\) \[ - - - \] D -](#)

Fluxes (J): [B 7.20 \(-\) D -](#)

**Identifiers (11) :**

<a href="#">NGC 7023</a>	<a href="#">IRAS 20599+6755</a>	<a href="#">LRN 487</a>	<a href="#">J0013021 0104.06+14.19</a>
<a href="#">C 2059+679</a>	<a href="#">IRAS F20599+6755</a>	<a href="#">OCISM 50</a>	<a href="#">AAVSO 2044+67</a>
<a href="#">Cl VDB 139</a>	<a href="#">LRN 104.08+14.21</a>	<a href="#">OCI 235</a>	

**Plots and Images**

radius  arcmin

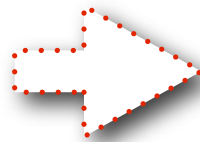
**References (371 between 1983 and 2009)**

*Simbad bibliographic survey began in 1950 for stars (at least bright stars) and in 1983 for all other objects (outside the solar system).*

from:  to:



### ADS Faceted Topic Search (alpha)



PAH

e.g.: "dark energy", "extrasolar planets", "weak lensing", "spin hall"

**Keyword Search:**

- Most relevant
- Most recent
- Most important

**Subject Area Search:**

- Most popular
- Most useful
- Most instructive

[ADS Home](#) | [Abstract Search](#) | [Help](#)

*“alpha” Faceted Topic Search in ADS  
(courtesy of Michael Kurtz & Alberto Accomazzi)*

ADS Query Results

http://adsres.cfa.harvard.edu/cgi-bin/topicFacetSearch?q=PAH;qtype=RELEVANT

SAO/NASA Astrophysics Data System (ADS)

Query Results from the ADS Database [Go to bottom of page](#)

Related Objects

- [M 82 \(14\)](#)
- [NGC 7027 \(12\)](#)
- [NGC 7023 \(10\)](#)
- [NAME ORION BAR \(10\)](#)
- [NAME RED RECTANGLE \(9\)](#)
- [OSO 81254-571 \(8\)](#)
- [NGC 2023 \(8\)](#)
- [NGC 253 \(8\)](#)
- [M 17 \(8\)](#)
- [PN G093.9-00.1 \(7\)](#)
- [NGC 7214 \(7\)](#)
- [IC 4553 \(7\)](#)
- [NGC 6260 \(6\)](#)
- [NGC 292 \(5\)](#)
- [NAME RHO OPH REGION \(5\)](#)
- [NAME LMC \(5\)](#)
- [MCG+10-14-025 \(5\)](#)
- [4C 47.36A \(5\)](#)
- [VV 65 \(4\)](#)
- [SBSG 0335-052 \(4\)](#)
- [OSO 82300-086 \(4\)](#)
- [NGC 7331 \(4\)](#)
- [NGC 4151 \(4\)](#)
- [NGC 1808 \(4\)](#)
- [NGC 1097 \(4\)](#)
- [NAME CAMPBELL'S HYDROGEN STAR \(4\)](#)
- [Mrk 273 \(4\)](#)
- [M 81 \(4\)](#)
- [M 42 \(4\)](#)
- [GSC 02342-00359 \(4\)](#)
- [KIB20031.G29.957-0.018 \(3\)](#)
- [KIB20031.G23.955+0.150 \(3\)](#)

Selected and retrieved 200 abstracts. [Sort options](#)

#	Bibcode Authors	Score Title	Date	<a href="#">List of Links</a> <a href="#">Access Control Help</a>	
1	<input type="checkbox"/> <a href="#">2007ApJ...657..810D</a> Draine, B. T.; Li, Aigen	100.000 Infrared Emission from Interstellar Dust. IV. The Silicate-Graphite-PAH Model in the Post-Spitzer Era	Mar 2007	<a href="#">A</a> <a href="#">E</a> <a href="#">E</a> <a href="#">X</a>	<a href="#">B</a> <a href="#">C</a> <a href="#">c</a> <a href="#">S</a> <a href="#">N</a> <a href="#">Q</a> <a href="#">U</a>
2	<input type="checkbox"/> <a href="#">2007ApJ...663..866D</a> Draine, B. T.; Dale, D. A.; Bendo, G.; Gordon, K. D.; Smith, J. D. T.; Armus, L.; Engelbracht, C. W.; Helou, G.; Kennicutt, R. C., Jr.; Li, A.; and 10 coauthors	96.842 Dust Masses, PAH Abundances, and Starlight Intensities in the SINGS Galaxy Sample	Jul 2007	<a href="#">A</a> <a href="#">E</a> <a href="#">E</a> <a href="#">X</a>	<a href="#">B</a> <a href="#">C</a> <a href="#">c</a> <a href="#">S</a> <a href="#">N</a> <a href="#">U</a>
3	<input type="checkbox"/> <a href="#">2007ApJ...654L..49S</a> Spoon, H. W. W.; Marshall, J. A.; Houck, J. R.; Elitzur, M.; Hao, L.; Armus, L.; Brandl, B. R.; Charmandaris, V.	95.232 Mid-Infrared Galaxy Classification Based on Silicate Obscuration and PAH Equivalent Width	Jan 2007	<a href="#">A</a> <a href="#">E</a> <a href="#">E</a> <a href="#">X</a>	<a href="#">B</a> <a href="#">C</a> <a href="#">c</a> <a href="#">S</a> <a href="#">N</a> <a href="#">U</a>
4	<input type="checkbox"/> <a href="#">2005ApJ...628L..29E</a> Engelbracht, C. W.; Gordon, K. D.; Rieke, G. H.; Werner, M. W.; Dale, D. A.; Latter, W. B.	95.090 Metallicity Effects on Mid-Infrared Colors and the 8 $\mu$ m PAH Emission in Galaxies	Jul 2005	<a href="#">A</a> <a href="#">E</a> <a href="#">E</a> <a href="#">X</a>	<a href="#">B</a> <a href="#">C</a> <a href="#">c</a> <a href="#">S</a> <a href="#">N</a> <a href="#">U</a>

Open "http://www.worldwidetelescope.org/wwtweb/goto.aspx?object=NGC6260&ra=21.026913&dec=-68.163300" in a new window

list of objects with links to WWT browser  
(thanks to ADS team & Jonathan Fay)

And now we got to NGC 7023 by using the literature as a filter.

The screenshot displays the Microsoft WorldWide Telescope Web Client interface. The browser window title is "Microsoft WorldWide Telescope Web Client". The address bar shows the URL <http://www.worldwidetelescope.org/webclient/default.aspx?wtml=http%3a%2f%2f> and a search bar with "Google". The navigation menu includes "Explore", "Guided Tours", "Search", "View", and "Settings". The breadcrumb trail reads "Collections > Open Collections > Link Collection >". A thumbnail for "NGC 7023" is visible in the top left. The main view is a large astronomical image of NGC 7023, a blue nebula. The bottom control panel features a "Look At" dropdown set to "Sky", an "Imagery" dropdown set to "Digitized Sky Survey (Optical)", and an "Info" icon. A thumbnail strip at the bottom left shows "Cepheus", "NGC 7023", and "NGC7023". On the right, a celestial globe shows the location in Cepheus with coordinates RA: 21h01m37s and Dec: 68:09:48. The status bar at the bottom left says "Done".

# NEWSROOM

- Press Releases
  - Chronological
  - By Subject
  - Outside Institutions
- What's Happening Archive
- Visuals
  - Image Use Policy
- Update Notifications
  - Mailing List
  - RSS Feed (XML)
- References
  - Fast Facts
  - Press Kit (.pdf)
  - Fact Sheet (.pdf)
  - Field Guides
  - Glossary
- Media Contacts

INTRODUCTION PRESS RELEASE VISUALS QUICK FACTS



Embedded Outflow in HH 46/47 Spitzer Space Telescope • IRAC  
NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech) 2003-06f

Credit: NASA/JPL-Caltech/A. Noriega-Crespo (SSC/Caltech), Digital Sky Survey

## HH46/47

This image from NASA's Spitzer Space Telescope transforms a dark cloud into a silky translucent veil, revealing the molecular outflow from an otherwise hidden newborn star. Using near-infrared light, Spitzer pierces through the dark cloud to detect the embedded outflow in an object called HH 46/47. Herbig-Haro (HH) objects are bright, nebulous regions of gas and dust that are usually buried within dark clouds. They are formed when supersonic gas ejected from a forming protostar, or embryonic star, interacts with the surrounding interstellar medium. These young stars are often detected only in the infrared.

The Spitzer image was obtained with the infrared array camera. Emission at 3.6 microns is shown as blue, emission from 4.5 and 5.8 microns has been combined as green, and 8.0 micron emission is depicted as red.

HH 46/47 is a striking example of a low-mass protostar ejecting a jet and creating a bipolar, jet-sided outflow. The protostellar

Seamlessness  
through...

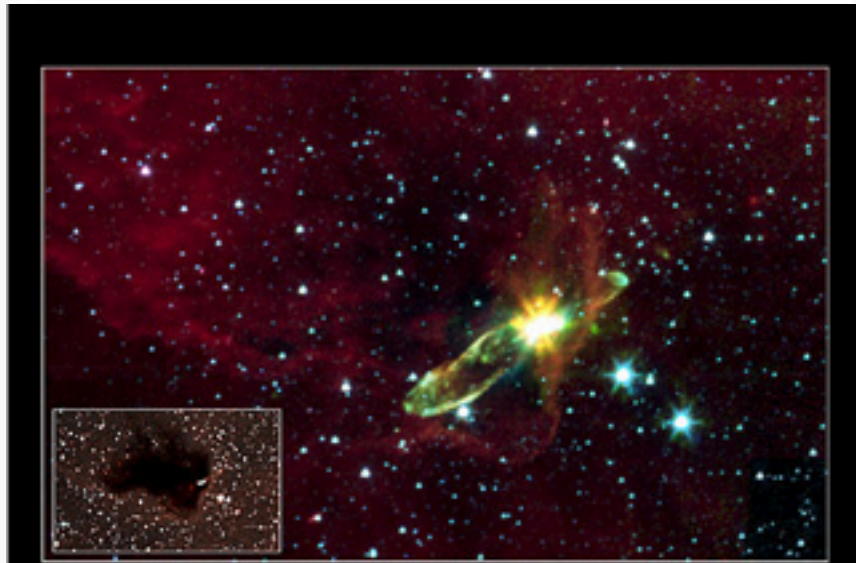
flickr  
+  
astrometry.net  
+  
WWT !?



# HH4647

Share This

- ADD FICKE
- SEND TO GROUP
- ADD TO SET
- BLOG THIS
- ALL SIZES
- ORDER PRINTS
- REDATE
- EDIT PHOTO
- DELETE



**Embedded Outflow in HH 46/47** Spitzer Space Telescope • IRAC  
IRAC, visible light (2003)  
 NASA / JPL-Caltech / A. Noriega-Orgaño (SSC/Caltech) src:2003-061

Uploaded on January 6, 2009 by Alyssa\_Goodman

**Alyssa\_Goodman's photostream**

16 uploads

browse

This photo also belongs to:

+ astrometry (Pool) x

- Tags**
- astrometry&et=version=10145 x
  - astrometry&et=id=alpha-200001-20029873 x
  - astrometry&et=status=solved x
- [Add a tag](#)

### Additional Information

- All rights reserved (edit)
- Anyone can see this photo (edit)
- Add to your map
- Taken on December 12, 2003 (edit)
- Photo stats
- Viewed 7 times (Not including you)
- Edit title, description, and tags

Flag your photo

Explore

Guided Tours

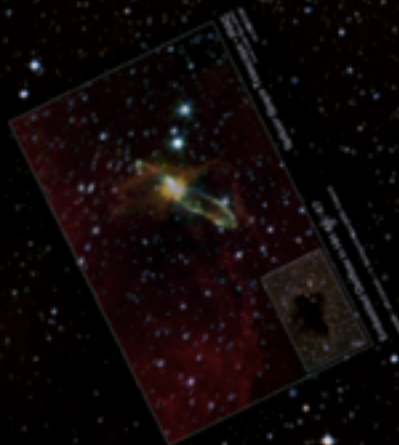
Search

View

Settings

Collections &gt; Open Collections &gt; HH4647 &gt;

1 of 1



Look At

Imagery

Info

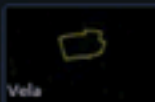
Image Crossfade

Sky

Digitized Sky Survey (Optical)

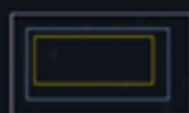


1 of 1

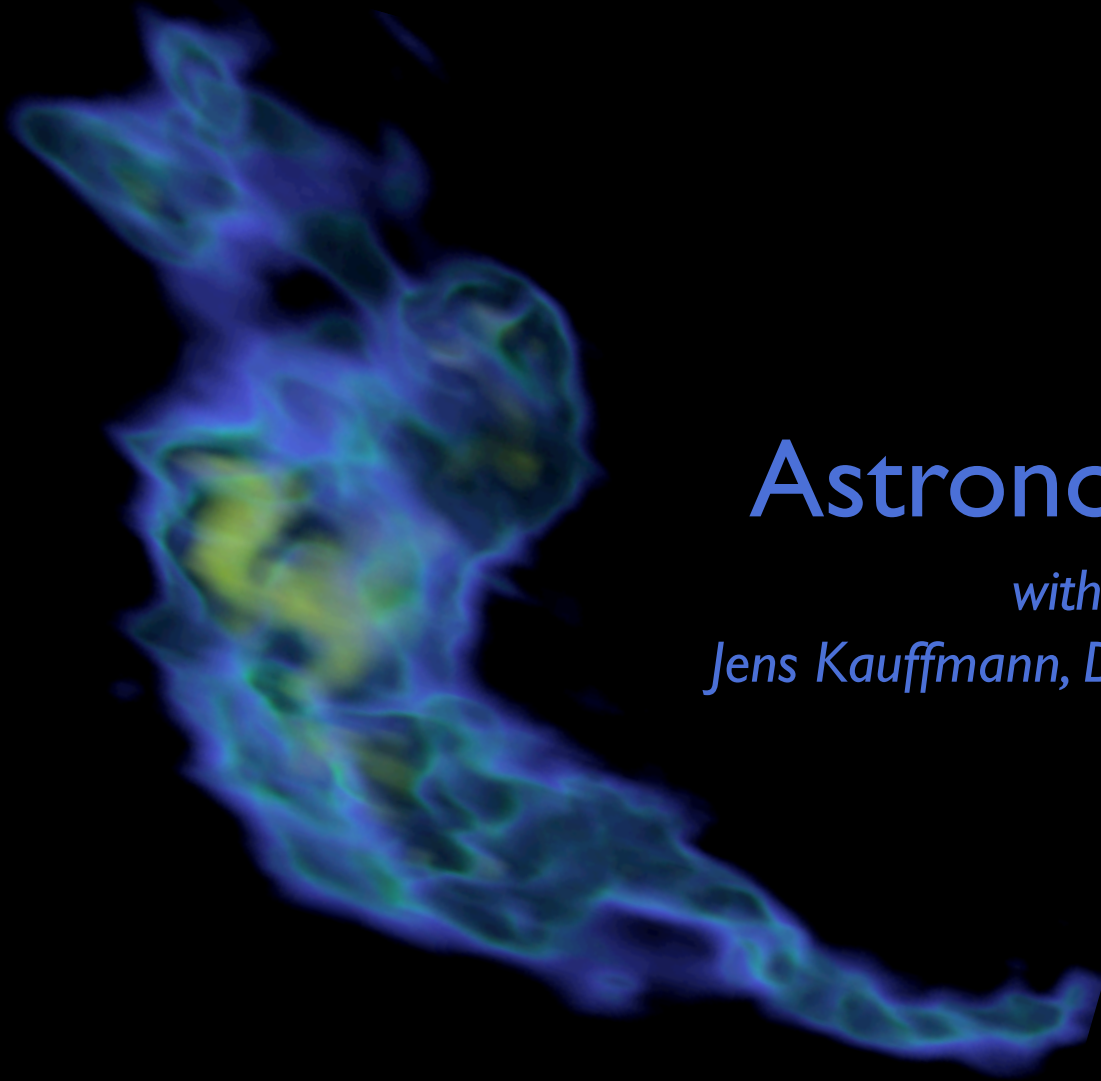


Vela

00:35:33

RA : 08h25m39s  
Dec : -51d01m10s

Done








# Astronomical Medicine

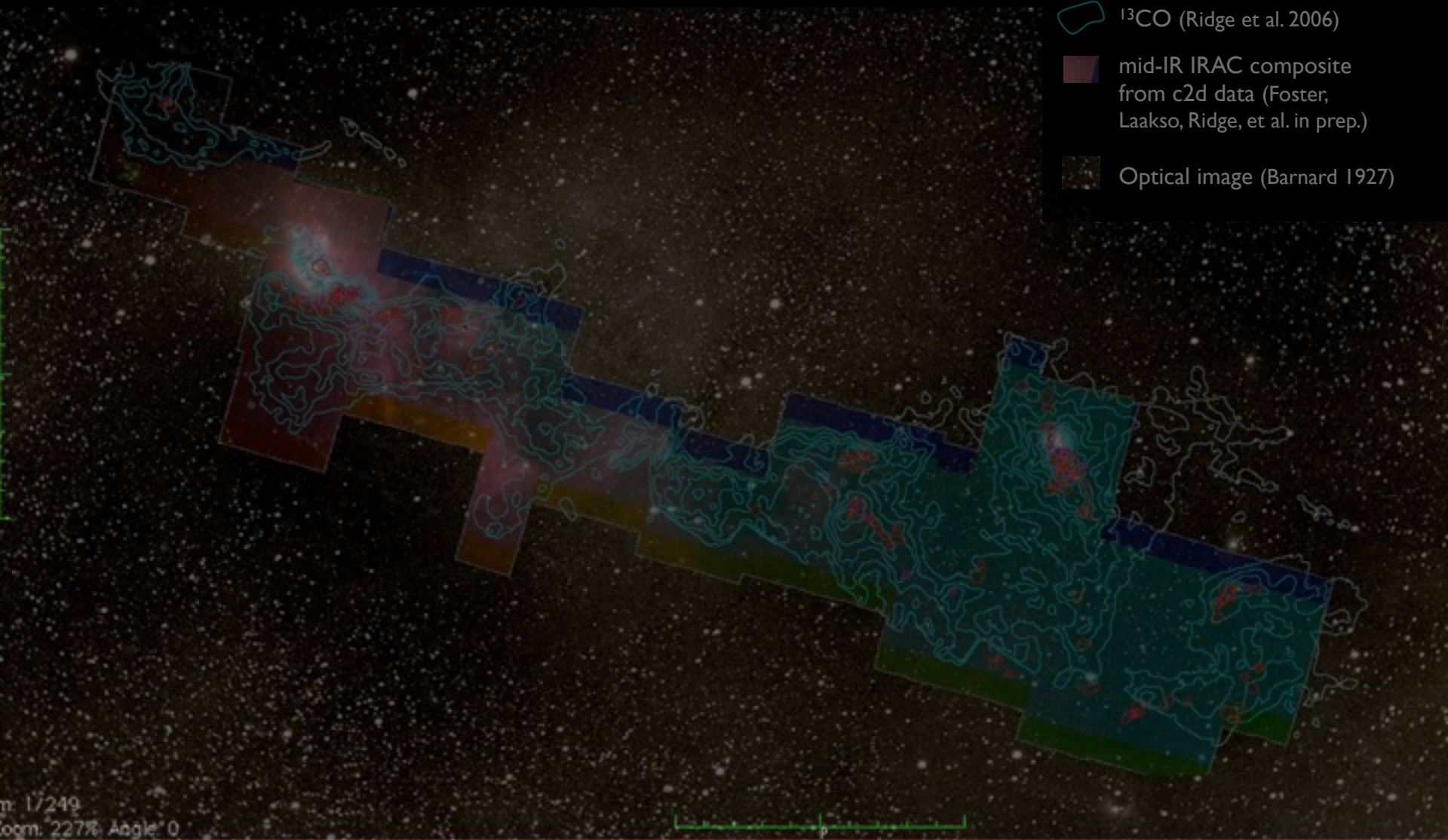
*with Michael Halle, Michelle Borkin,  
Jens Kauffmann, Douglas Alan, Erik Rosolowsky &  
Nick Holliman*

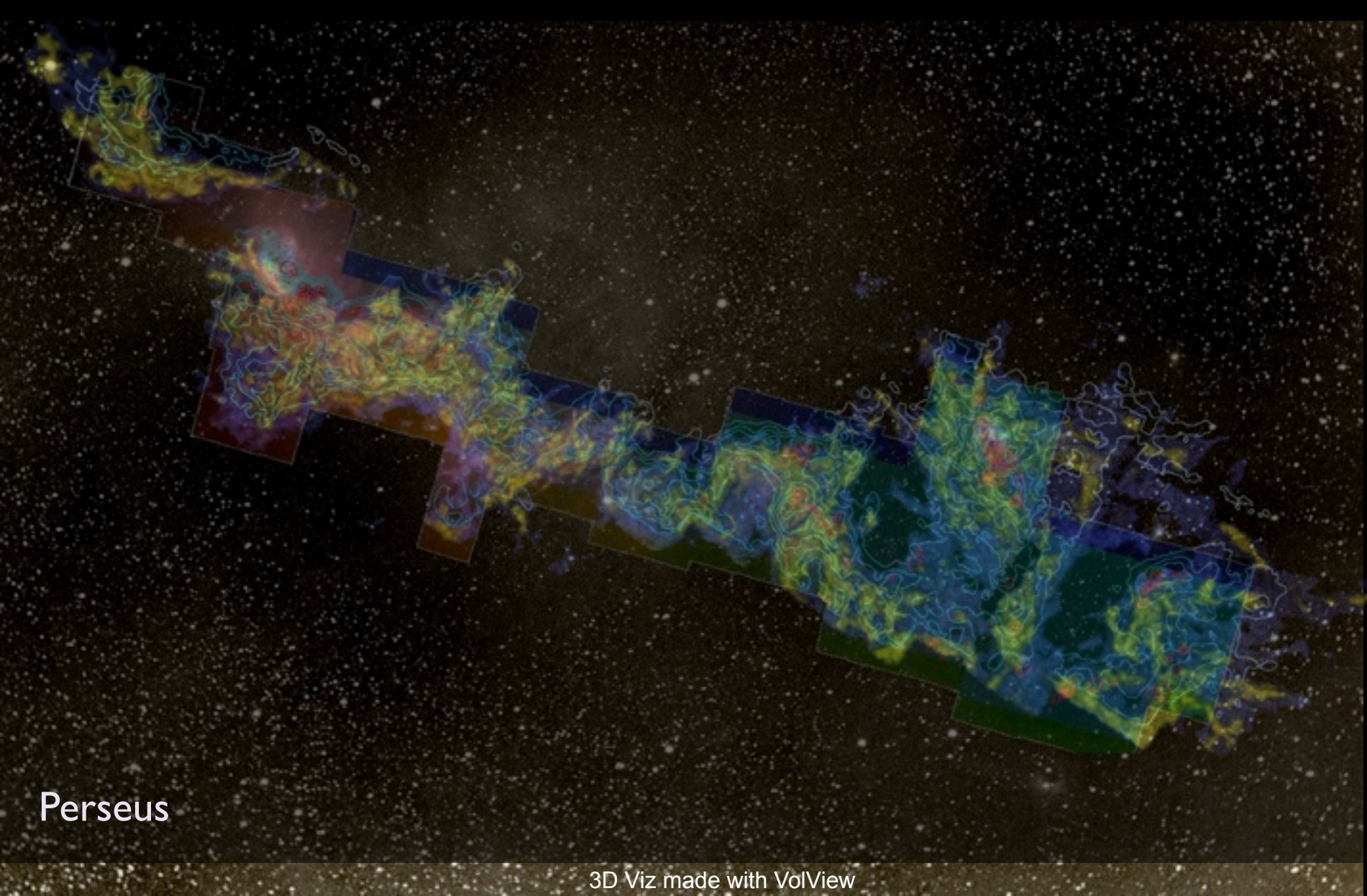


# COMPLETE Perseus

Image 1  
View size: 1305 x 733  
WL: 63 WW: 127

-  mm peak (Enoch et al. 2006)
-  sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
-   $^{13}\text{CO}$  (Ridge et al. 2006)
-  mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)
-  Optical image (Barnard 1927)





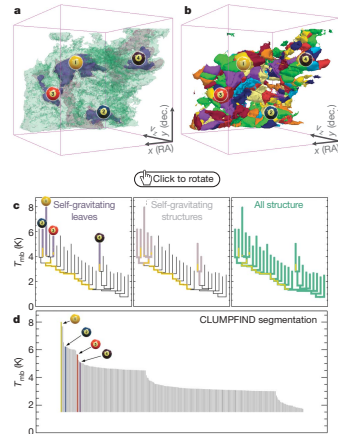
Perseus

3D Viz made with VolView

# 3D PDF (demo)

LETTERS

NATURE | Vol 457 | 1 January 2009



**Figure 2** | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to  $^{13}\text{CO}$  emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct self-gravitating leaves within them; and green corresponds to the surface in the data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of  $T_{\text{mb}}$  (main-beam temperature) test-level values for which the virial parameter is less than 2. The  $x$ - $y$  locations of the four 'self-gravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position-position-velocity ( $p$ - $p$ - $v$ ) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (**c**) to track hierarchical structure, **d** shows a pseudo-dendrogram of the CLUMPFIND segmentation (**b**), with the same four labels used in Fig. 1 and in **a**. As 'clumps' are not allowed to belong to larger structures, each pseudo-branch in **d** is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in **b** because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (**a** and **b**) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the 'home' view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front ( $-0.5 \text{ km s}^{-1}$ ) to back ( $8 \text{ km s}^{-1}$ ).

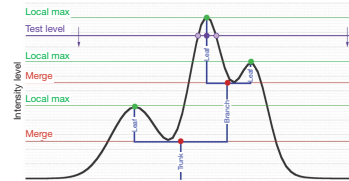
data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND's two free parameters, the same molecular-line data set<sup>3</sup> can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, 'structure trees'<sup>9</sup> were proposed as a way to characterize clouds' hierarchical structure

using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D ( $p$ - $p$ - $v$ ) data cube into an easily visualized representation called a 'dendrogram'<sup>10</sup>. Although well developed in other data-intensive fields<sup>11,12</sup>, it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency<sup>13</sup>.

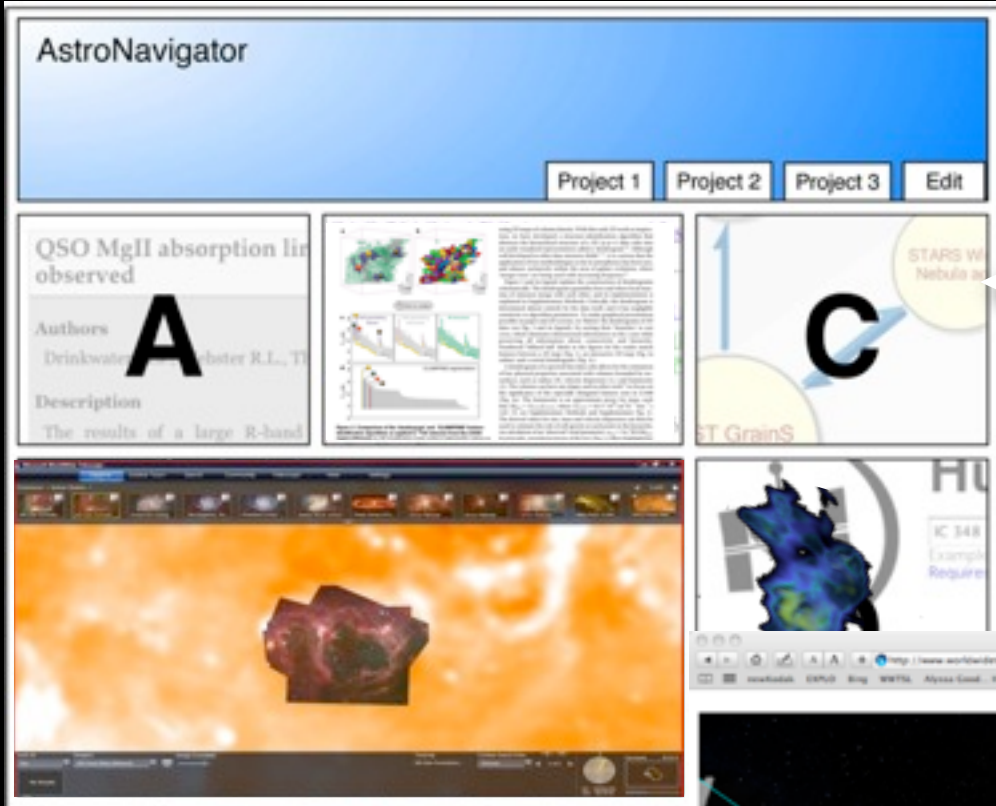
Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we 'flatten' the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their 'branches' to not cross, which eliminates dimensional information on the  $x$  axis while preserving all information about connectivity and hierarchy. Numbered 'billiard ball' labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by iso-surfaces, such as radius ( $R$ ), velocity dispersion ( $\sigma_v$ ) and luminosity ( $L$ ). The volumes can have any shape, and in other work<sup>14</sup> we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that  $M_{\text{lum}} = X_{13\text{CO}} L_{13\text{CO}}$ , where  $X_{13\text{CO}} = 8.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ s}$  (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an 'observed' virial parameter,  $\alpha_{\text{obs}} = 5\sigma_v^2 R / GM_{\text{lum}}$ . In principle, extended portions of the tree (Fig. 2, yellow highlighting) where  $\alpha_{\text{obs}} < 2$  (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of  $p$ - $p$ - $v$  space where self-gravity is significant. As  $\alpha_{\text{obs}}$  only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields<sup>16</sup>, its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

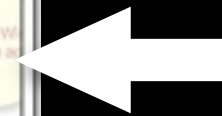


**Figure 3** | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an iso-surface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from 'isosurface' rather than 'point' intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

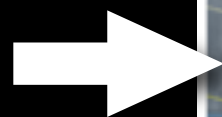




Fiction  
(for now)



Fact  
(right now)





# Astronomical Data and Information Visualization

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# Astronomical Data and Information Visualization

Organization, Anarchy, or  
Organized Anarchy?

