The Legacy of the *Spitzer* c2d Legacy Project

Mike Dunham, Yale University

Neal Fest: Observing the Universe from Molecules to Galaxies
The University of Texas at Austin
Thursday, April 25, 2013

A *Spitzer Space Telescope* Legacy Survey

From Molecular Cores to Planet Forming Disks

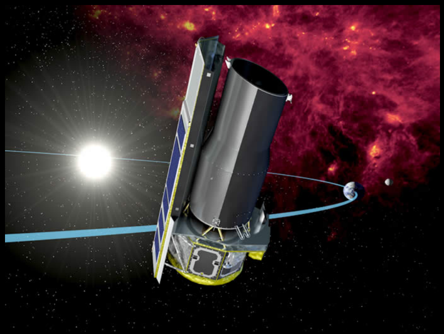
↓

Cores to Disks

↓

c2d

The c2d survey



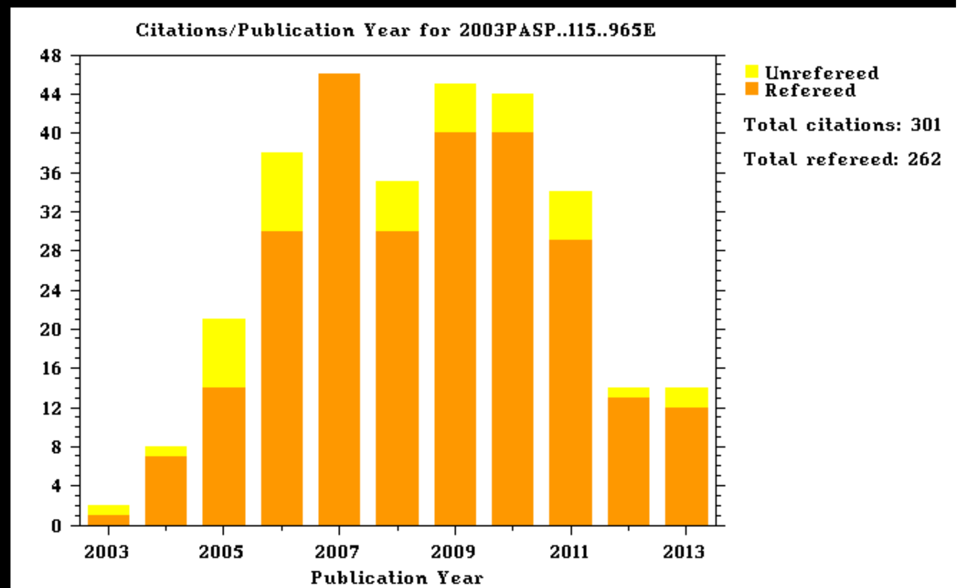
- One of the original six *Spitzer* legacy surveys
- IR imaging (3.6 – 160 microns) of 5 large, nearby molecular clouds, ~100 isolated dense cores, >150 wTTS
- IR spectroscopy (5 – 40 μm) of selected targets (some selected after imaging)
- Complementary data at optical and (sub)mm wavelengths
- Follow evolution from starless cores to planet-forming disks:

Publications of the Astronomical Society of the Pacific, 115:965–980, 2003 August

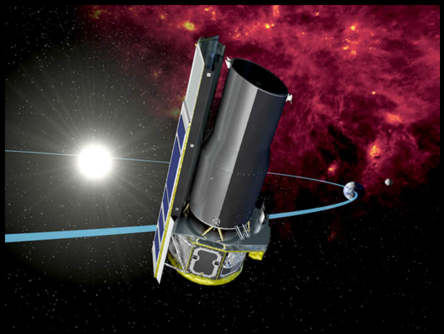
From Molecular Cores to Planet-forming Disks: An *SIRTF* Legacy Program

Neal J. Evans II,[1] Lori E. Allen,[2] Geoffrey A. Blake,[3] A. C. A. Boogert,[4] Tyler Bourke,[2] Paul M. Harvey,[1] J. E. Kessler,[5] David W. Koerner,[6] Chang Won Lee,[7] Lee G. Mundy,[8] Philip C. Myers,[2] Deborah L. Padgett,[9] K. Pontoppidan,[10] Anneila I. Sargent,[4] Karl R. Stapelfeldt,[11] Ewine F. van Dishoeck,[10] Chadwick H. Young,[1] and Kaisa E. Young[1]
Received 2003 March 6; accepted 2003 April 18

ABSTRACT. Crucial steps in the formation of stars and planets can be studied only at mid- to far-infrared wavelengths, where the *Space Infrared Telescope* (*SIRTF*) provides an unprecedented improvement in sensitivity. We will use all three *SIRTF* instruments (Infrared Array Camera [IRAC], Multiband Imaging Photometer for *SIRTF* [MIPS], and Infrared Spectrograph [IRS]) to observe sources that span the evolutionary sequence from molecular cores to protoplanetary disks, encompassing a wide range of cloud masses, stellar masses, and star-forming environments. In addition to targeting about 150 known compact cores, we will survey with IRAC and MIPS (3.6–70 μm) the entire areas of five of the nearest large molecular clouds for new candidate protostars and substellar objects as faint as 0.001 solar luminosities. We will also observe with IRAC and MIPS about 190 systems likely to be in the early stages of planetary system formation (ages up to about 10 Myr), probing the evolution of the circumstellar dust, the raw material for planetary cores. Candidate planet-forming disks as small as 0.1 lunar masses will be detectable. Spectroscopy with IRS of new objects found in the surveys and of a select group of known objects will add vital information on the changing chemical and physical conditions in the disks and envelopes. The resulting data products will include catalogs of thousands of previously unknown sources, multiwavelength maps of about 20 deg^2 of molecular clouds, photometry of about 190 known young stars, spectra of at least 170 sources, ancillary data from ground-based telescopes, and new tools for analysis and modeling. These products will constitute the foundations for many follow-up studies with ground-based telescopes, as well as with *SIRTF* itself and other space missions such as *SIM*, *JWST*, *Herschel*, and *TPF*/*Darwin*.



The c2d survey



- One of the original six *Spitzer* legacy surveys
- IR imaging (3.6 – 160 microns) of 5 large, nearby molecular clouds, ~100 isolated dense cores, >150 wTTS
- IR spectroscopy (5 – 40 μm) of selected targets (some selected after imaging)
- Complementary data at optical and (sub)mm wavelengths
- Follow evolution from starless cores to planet-forming disks:
  - Are starless cores truly starless?
  - How quickly do young stars move through the evolutionary sequence?
  - At what rates are nearby regions forming new stars?
  - Where do young stars form (spatial and environment)?
  - How do disk properties (and presence) evolve with time?
  - How does the chemical composition of dust and ices in young (proto)stellar systems evolve? (see talk by Ewine van Dishoeck: “Dust, ice, and gas: from c2d and DIGIT to ALMA”)

c2d Science Results

Are Starless Cores Truly Starless?

The Astrophysical Journal Supplement Series, 154:396–401, 2004 September

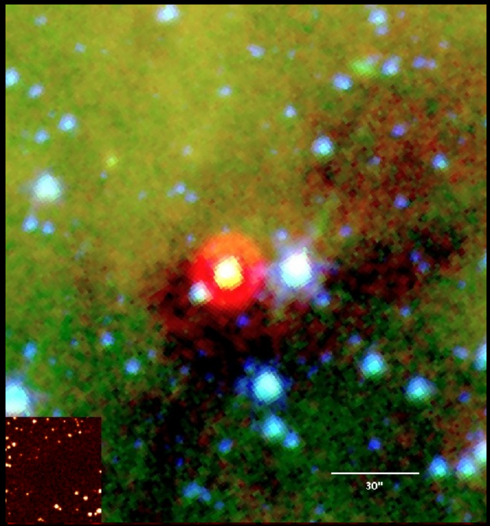
A "STARLESS" CORE THAT ISN'T: DETECTION OF A SOURCE IN THE L1014 DENSE CORE WITH THE *SPITZER SPACE TELESCOPE*

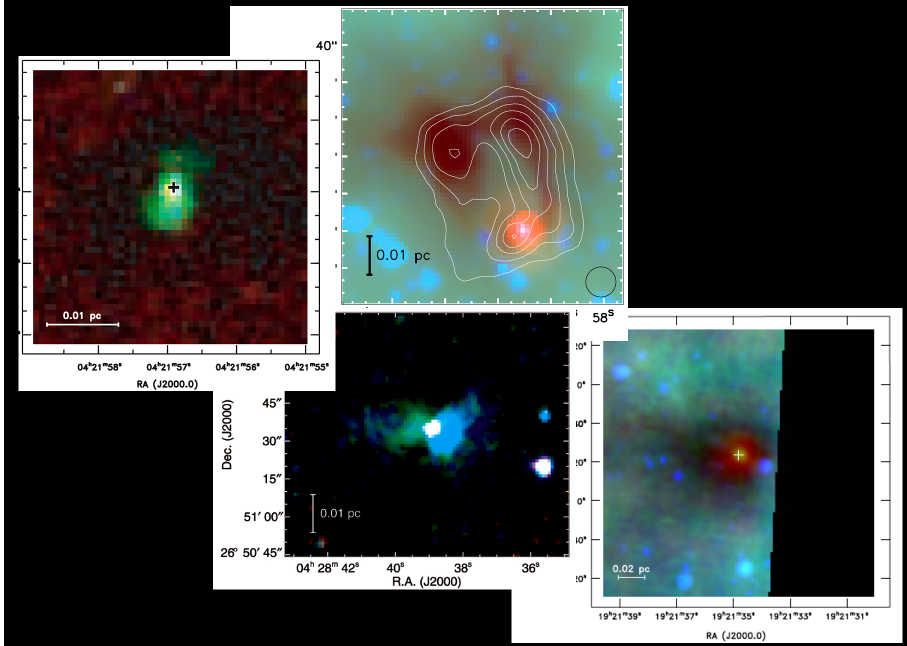
Chadwick H. Young,[1] Jes K. Jørgensen,[2] Yancy L. Shirley,[3] Jens Kauffmann,[4] Tracy Huard,[5] Shih-Ping Lai,[6] Chang Won Lee,[7] Antonio Crapsi,[5] Tyler L. Bourke,[8] Cornelis P. Dullemond,[9] Timothy Y. Brooke,[10] Alicia Porras,[5] William Spiesman,[1] Lori E. Allen,[5] Geoffrey A. Blake,[11] Neal J. Evans II,[1] Paul M. Harvey,[1] David W. Koerner,[12] Lee G. Mundy,[6] Phillip C. Myers,[5] Deborah L. Padgett,[13] Anneila I. Sargent,[10] Karl R. Stapelfeldt,[14] Ewine F. van Dishoeck,[2] Frank Bertoldi,[4] Nicholas Chapman,[6] Lucas Cieza,[1] Christopher H. DeVries,[5] Naomi A. Ridge,[5] and Zahed Wahhaj[12]
Received 2004 March 26; accepted 2004 April 24

ABSTRACT

We present observations of L1014, a dense core in the Cygnus region previously thought to be starless, but data from the *Spitzer Space Telescope* show the presence of an embedded source. We propose a model for this source that includes a cold core, heated by the interstellar radiation field, and a low-luminosity internal source. The low luminosity of the internal source suggests a substellar object. If L1014 is representative, other "starless" cores may turn out to harbor central sources.

Subject headings: infrared: stars — ISM: individual (L1014) — stars: formation — stars: low-mass, brown dwarfs





The Astrophysical Journal Supplement Series, 179:249–282, 2008 November

IDENTIFYING THE LOW-LUMINOSITY POPULATION OF EMBEDDED PROTOSTARS IN THE c2d OBSERVATIONS OF CLOUDS AND CORES

Michael M. Dunham,[1] Antonio Crapsi,[2,3] Neal J. Evans II,[1] Tyler L. Bourke,[4] Tracy L. Huard,[4] Philip C. Myers,[4] and Jens Kauffmann[4,5]
Received 2008 February 2; accepted 2008 June 10

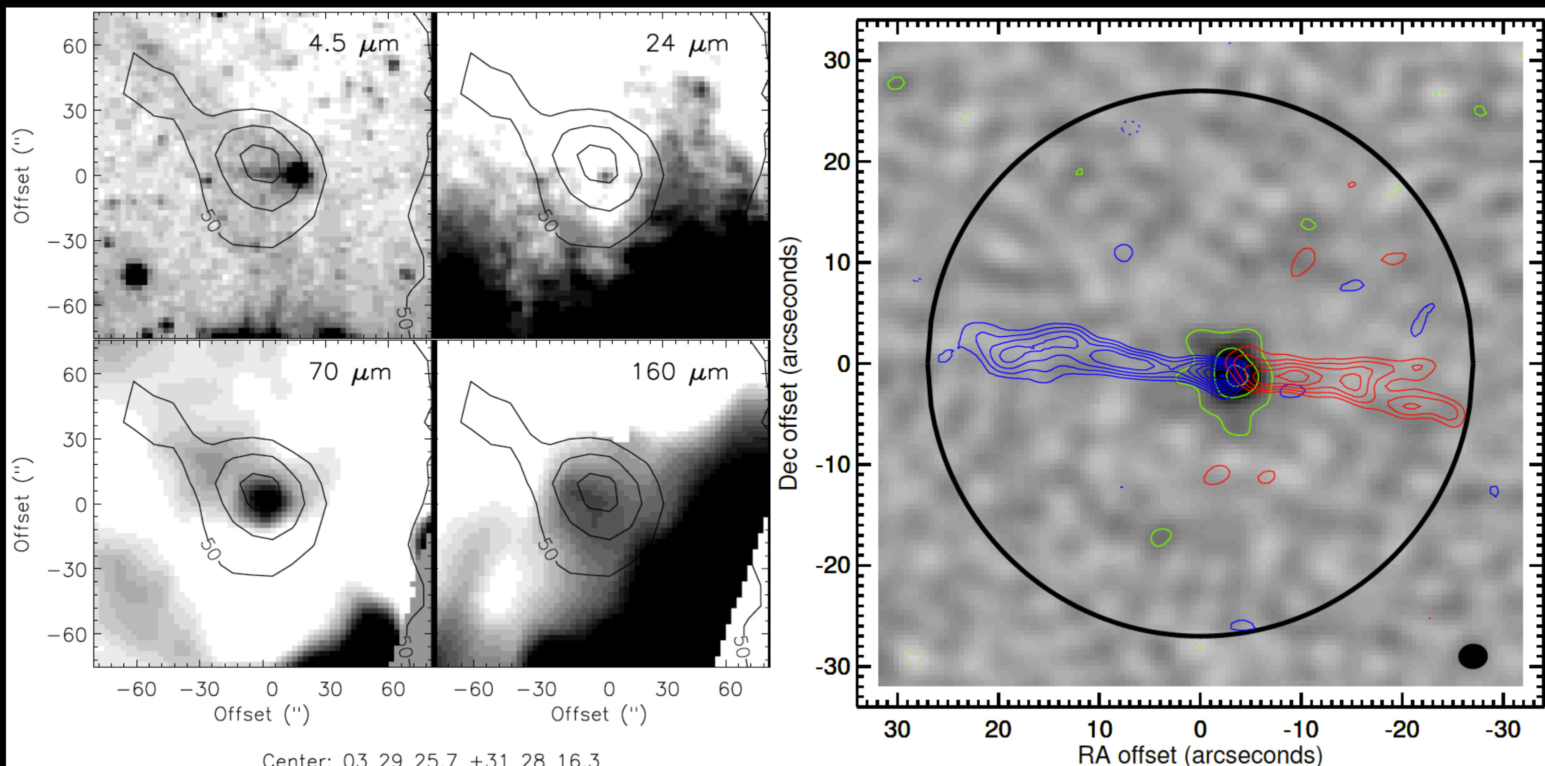
ABSTRACT

We present the results of a search for all embedded protostars with internal luminosities $\leq 1.0\ L_\odot$ in the full sample of nearby, low-mass star-forming regions surveyed by the *Spitzer Space Telescope* Legacy Project "From Molecular Cores to Planet Forming Disks" (c2d). The internal luminosity of a source, L_{int}, is the luminosity of the central source and excludes luminosity arising from external heating. On average, the *Spitzer* c2d data are sensitive to embedded protostars with $L_{int} \geq 4 \times 10^{-3}(d/140\ \mathrm{pc})^2\ L_\odot$, a factor of 25 better than the sensitivity of the *Infrared Astronomical Satellite* (*IRAS*) to such objects. We present a set of selection criteria used to identify candidates from the *Spitzer* data and examine complementary data to decide whether each candidate is truly an embedded protostar. We find a tight correlation between the 70 μm flux and internal luminosity of a protostar, an empirical result based on both observations and detailed two-dimensional radiative transfer models of protostars. We identify 50 embedded protostars with $L_{int} \leq 1.0\ L_\odot$; 15 have $L_{int} \leq 0.1\ L_\odot$. The intrinsic distribution of source luminosities increases to lower luminosities. While we find sources down to the above sensitivity limit, indicating that the distribution may extend to luminosities lower than probed by these observations, we are able to rule out a continued rise in the distribution below $L_{int} = 0.1\ L_\odot$. Between 75% and 85% of cores classified as starless prior to being observed by *Spitzer* remain starless to our luminosity sensitivity; the remaining 15%–25% harbor low-luminosity, embedded protostars. We compile complete spectral energy distributions for all 50 objects and calculate standard evolutionary signatures (L_{bol}, T_{bol}, and L_{bol}/L_{smm}) and argue that these objects are inconsistent with the simplest picture of star formation, wherein mass accretes from the core onto the protostar at a constant rate.

Subject headings: stars: formation — stars: low-mass, brown dwarfs

Online material: machine-readable table

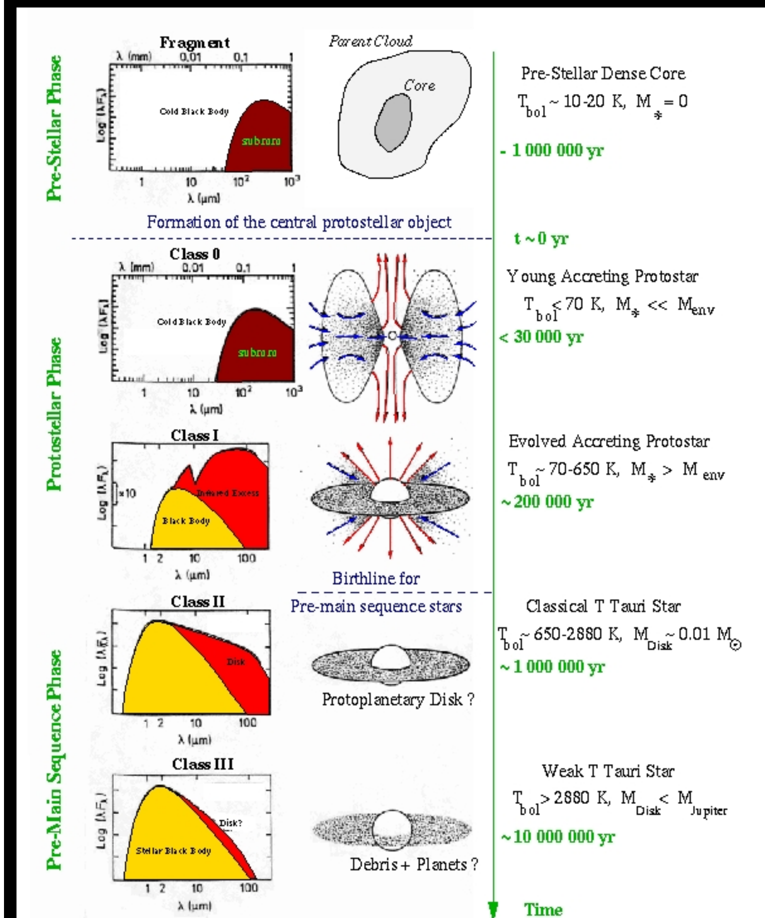
Are Starless Cores Truly Starless?

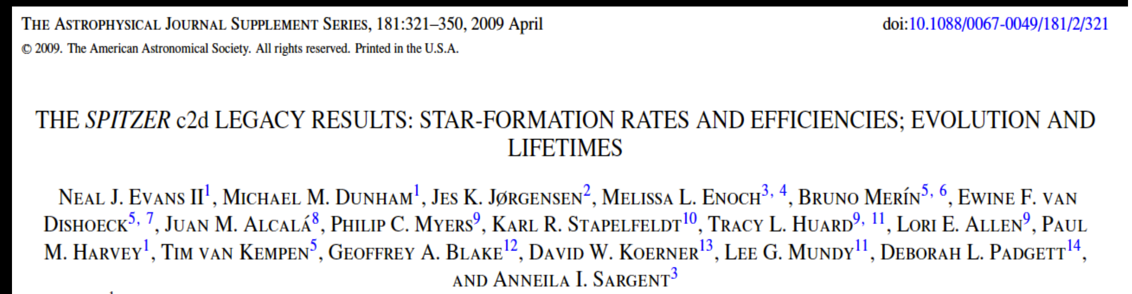


Enoch et al. (2010), Dunham et al. (2011)

Chen et al. (2010), Pineda et al. (2011), Schnee et al. (2012),
Chen et al. (2012), Pezzuto et al. (2012), Murillo & Lai (2013), Huang & Hirano (2013)

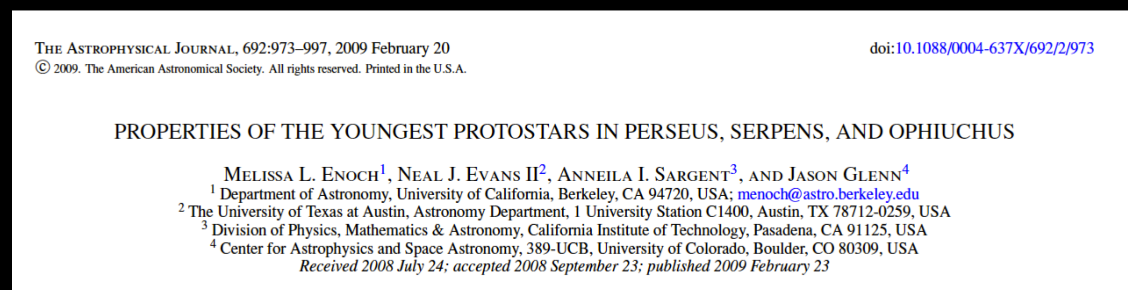
How Quickly do Young Stars Move Through the Evolutionary Sequence?




The Astrophysical Journal Supplement Series, 181:321–350, 2009 April doi:10.1088/0067-0049/181/2/321

THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

Neal J. Evans II[1], Michael M. Dunham[1], Jes K. Jørgensen[2], Melissa L. Enoch[3, 4], Bruno Merín[5, 6], Ewine F. van Dishoeck[5, 7], Juan M. Alcalá[8], Philip C. Myers[9], Karl R. Stapelfeldt[10], Tracy L. Huard[9, 11], Lori E. Allen[9], Paul M. Harvey[1], Tim van Kempen[5], Geoffrey A. Blake[12], David W. Koerner[13], Lee G. Mundy[11], Deborah L. Padgett[14], and Anneila I. Sargent[3]


The Astrophysical Journal, 692:973–997, 2009 February 20 doi:10.1088/0004-637X/692/2/973

PROPERTIES OF THE YOUNGEST PROTOSTARS IN PERSEUS, SERPENS, AND OPHIUCHUS

Melissa L. Enoch[1], Neal J. Evans II[2], Anneila I. Sargent[3], and Jason Glenn[4]
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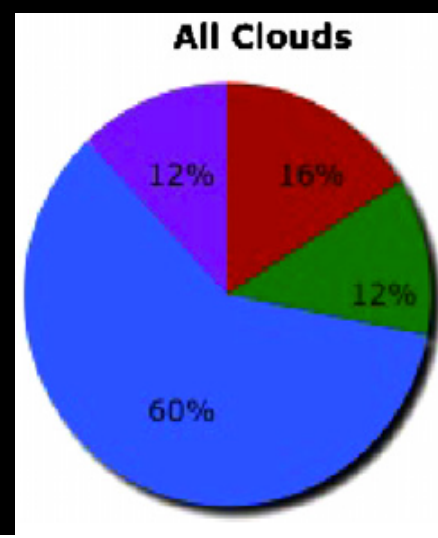
Received 2008 July 24; accepted 2008 September 23; published 2009 February 23



Where do Young Stars Form?

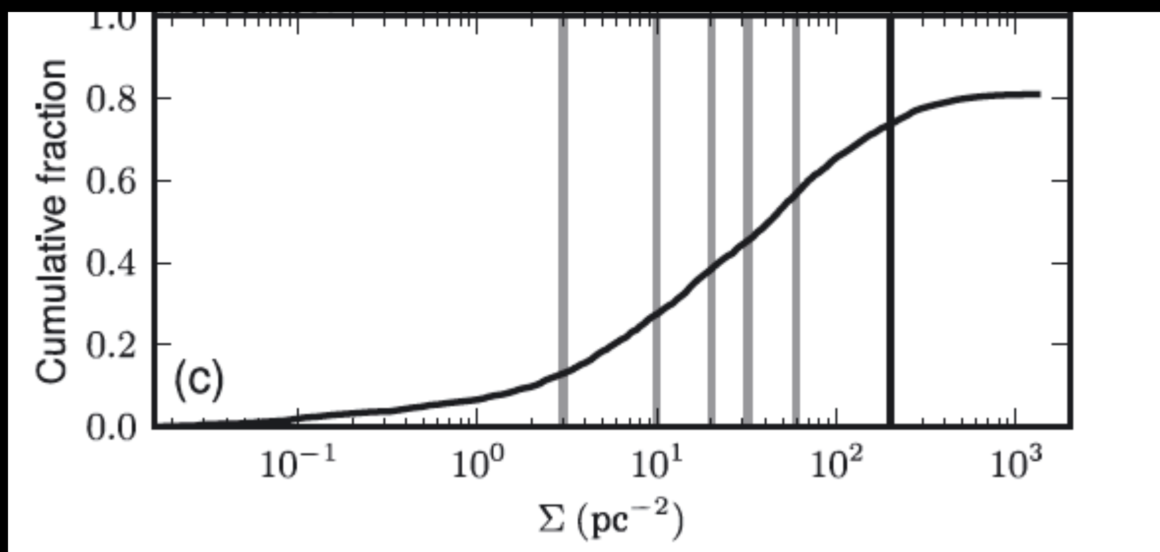
The Astrophysical Journal Supplement Series, 181:321–350, 2009 April doi:10.1088/0067-0049/181/2/321

THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

Neal J. Evans II[1], Michael M. Dunham[1], Jes K. Jørgensen[2], Melissa L. Enoch[3, 4], Bruno Merín[5, 6], Ewine F. van Dishoeck[5, 7], Juan M. Alcalá[8], Philip C. Myers[9], Karl R. Stapelfeldt[10], Tracy L. Huard[9, 11], Lori E. Allen[9], Paul M. Harvey[1], Tim van Kempen[5], Geoffrey A. Blake[12], David W. Koerner[13], Lee G. Mundy[11], Deborah L. Padgett[14], and Anneila I. Sargent[3]

Table 7
Sources by Class and Environment

Environment	Class I	Flat	Class II	Class III	Total	I+F/II+III
Distributed	11	7	43	32	93	0.24
Loose Group	28	5	30	7	70	0.89
Tight Group	34	25	64	8	131	0.82
Loose Cluster	127	112	559	131	929	0.35
Tight Cluster	90	79	322	63	554	0.44



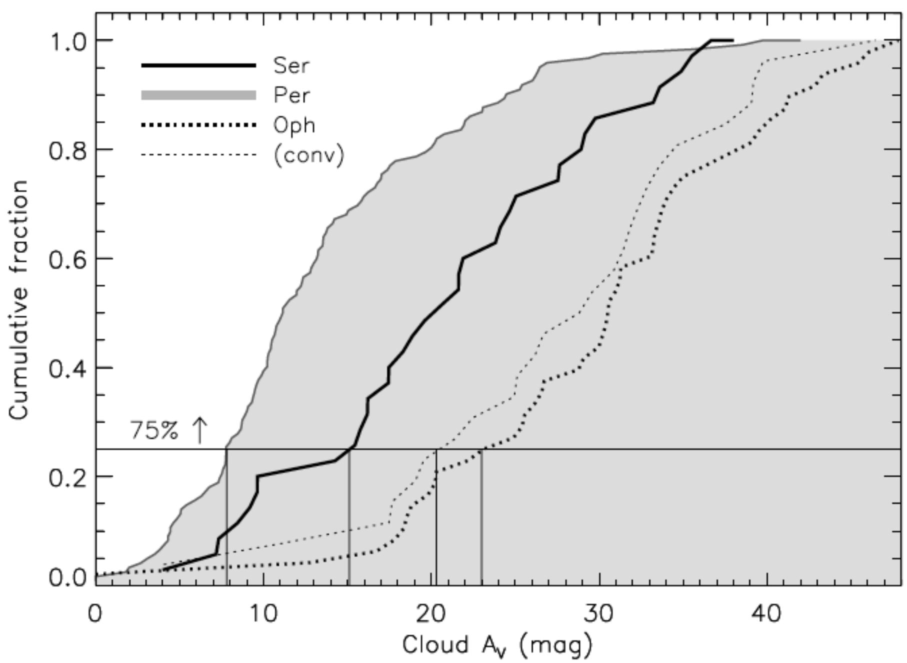
Bressert et al. (2010)

Where do Young Stars Form?

The Astrophysical Journal, 666:982–1001, 2007 September 10

COMPARING STAR FORMATION ON LARGE SCALES IN THE c2d LEGACY CLOUDS: BOLOCAM 1.1 mm DUST CONTINUUM SURVEYS OF SERPENS, PERSEUS, AND OPHIUCHUS

Melissa L. Enoch,[1] Jason Glenn,[2] Neal J. Evans II,[3] Anneila I. Sargent,[1] Kaisa E. Young,[3,4] and Tracy L. Huard[5]
Received 2006 November 4; accepted 2007 May 22



The Astrophysical Journal, 723:1019–1037, 2010 November 10
doi:10.1088/0004-637X/723/2/1019

THE STAR FORMATION RATE AND GAS SURFACE DENSITY RELATION IN THE MILKY WAY: IMPLICATIONS FOR EXTRAGALACTIC STUDIES

Amanda Heiderman[1], Neal J. Evans II[1], Lori E. Allen[2], Tracy Huard[3], and Mark Heyer[4]
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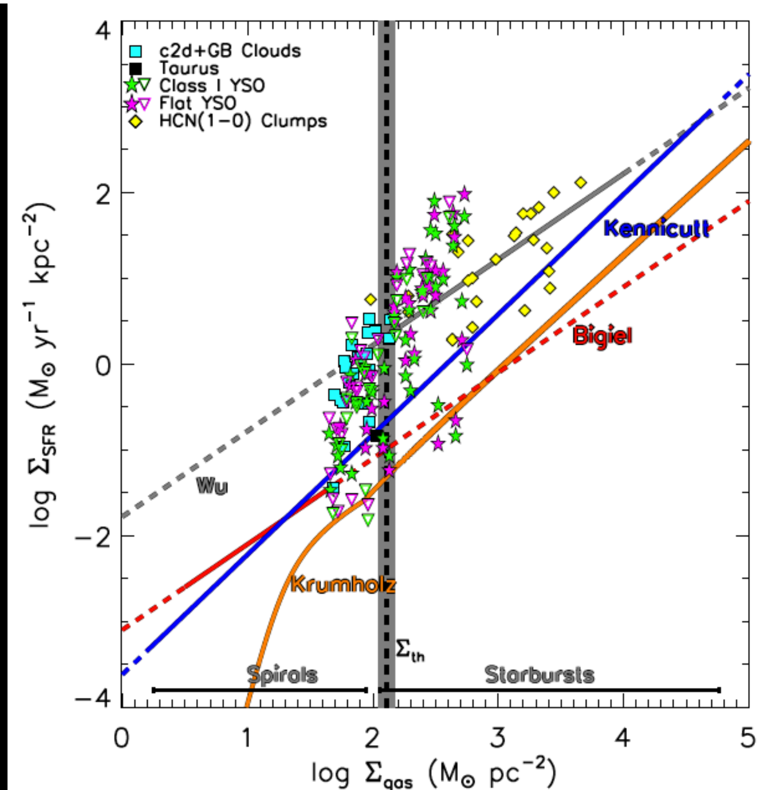
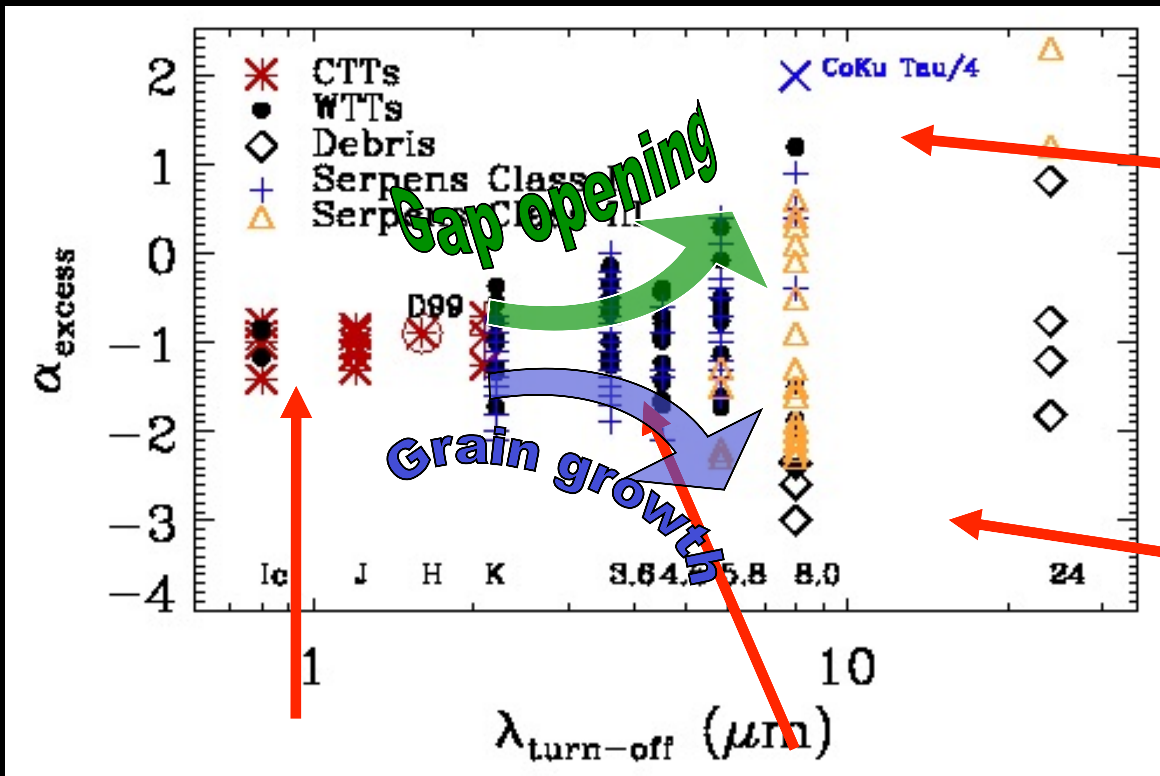
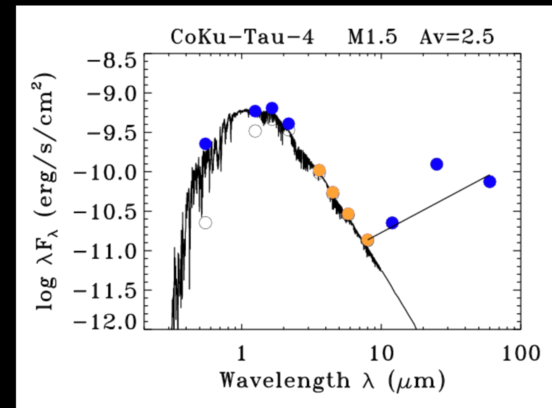
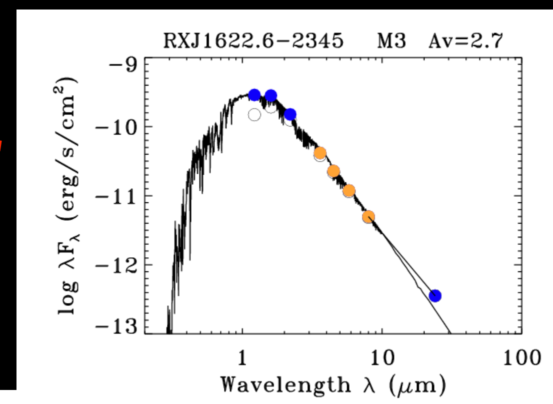
Received 2010 June 28; accepted 2010 September 4; published 2010 October 18

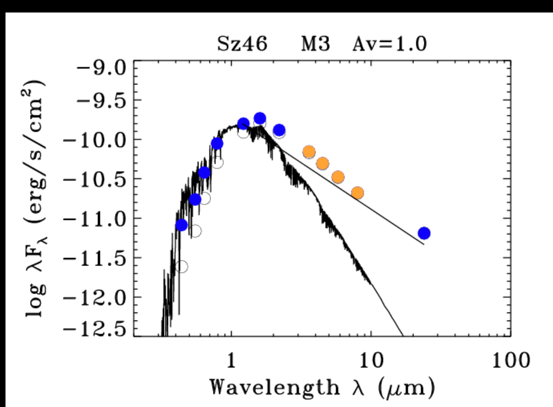


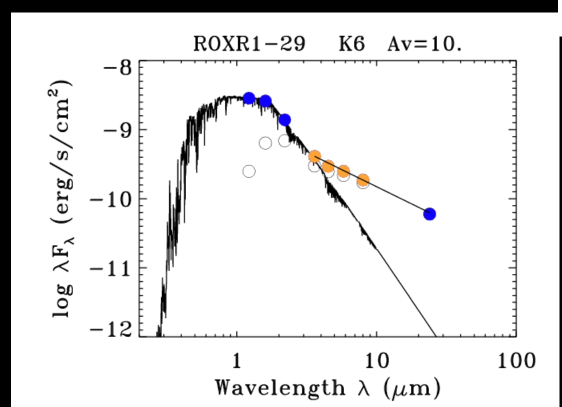
How Do Disks Evolve?











Cieza et al. (2007)
Merin et al. (2010)
Williams & Cieza (2010)

Slide Courtesy N. Evans

How Do Disks Evolve?

The Astrophysical Journal, 675: L109–L112, 2008 March 10

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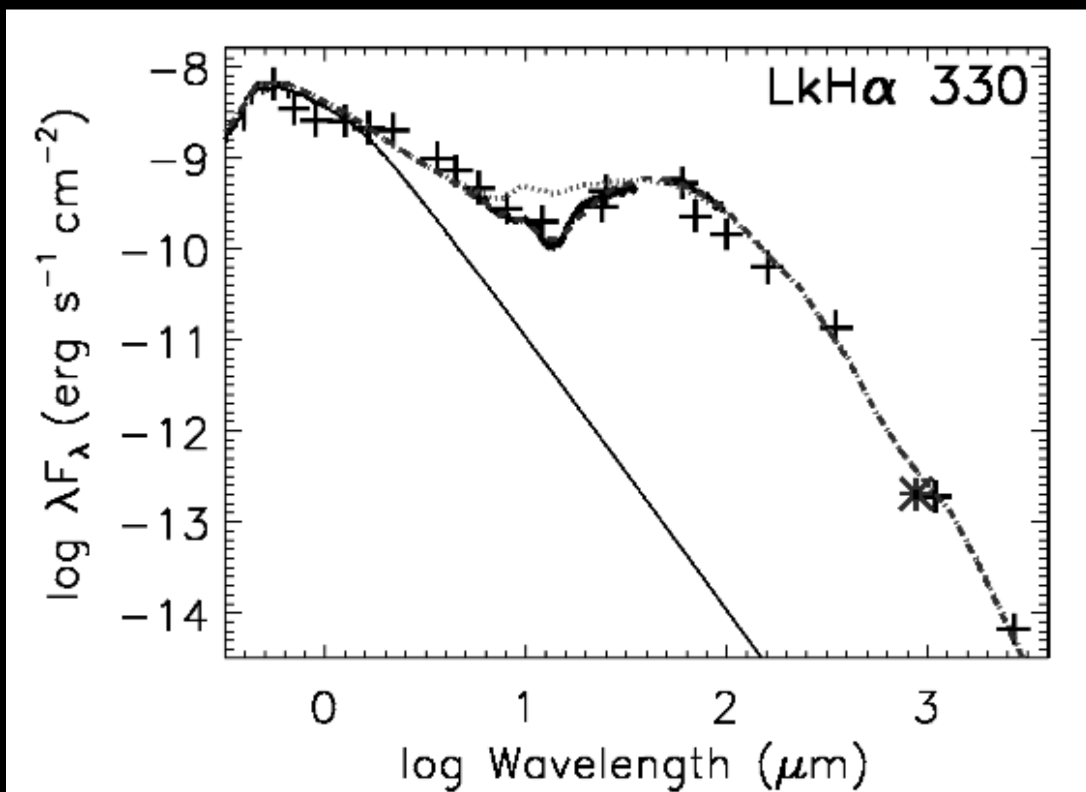
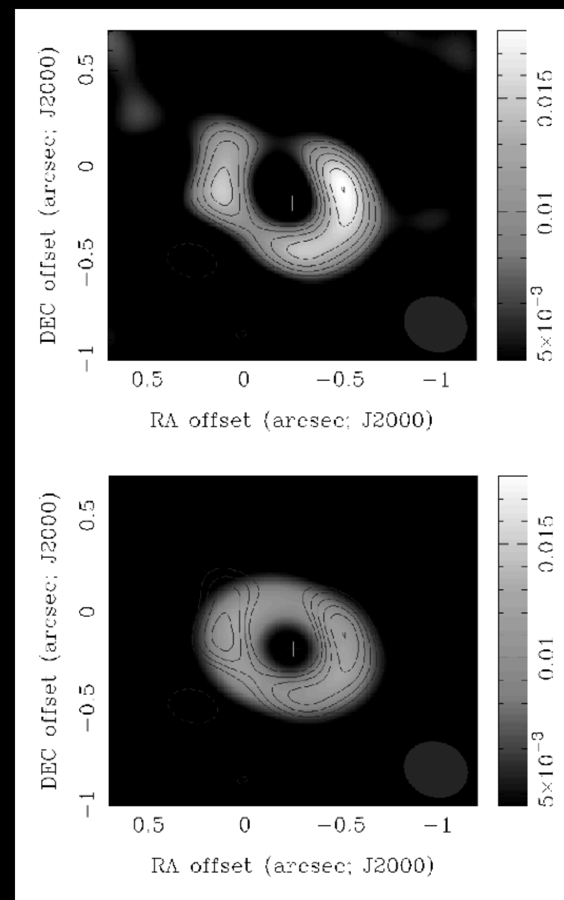
LkHα 330: EVIDENCE FOR DUST CLEARING THROUGH RESOLVED SUBMILLIMETER IMAGING

J. M. Brown,[1] G. A. Blake,[2] C. Qi,[3] C. P. Dullemond,[4] and D. J. Wilner[3]
Received 2007 December 20; accepted 2008 January 23; published 2008 February 19





The Legacy of c2d

Science Legacy

>75 papers

Star formation rates (and comparison to ex-gal relations), stellar mass assembly process, chemical inventory of star-forming regions, brown dwarf formation, dust properties and evolution, ...

Query Results from the ADS Database

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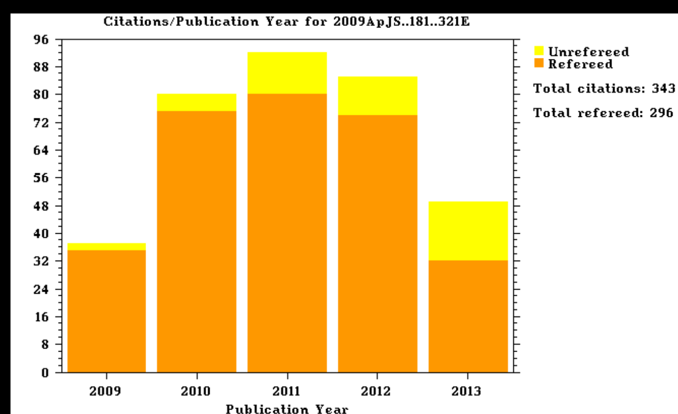
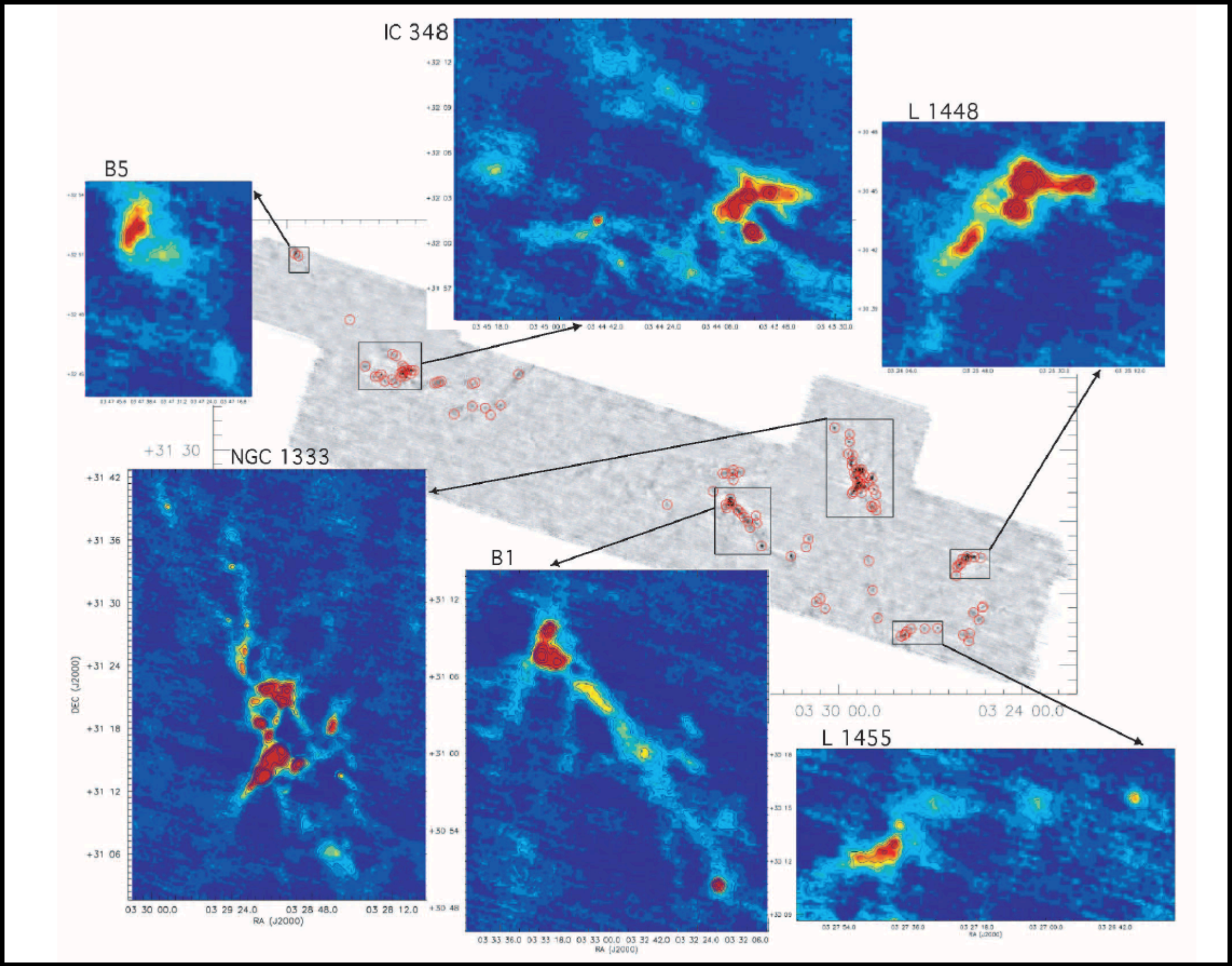
#	Bibcode / Authors	Cites / Title	Date	List of Links / Access Control Help
1	2009ApJS..181..321E Evans, Neal J., II; Dunham, Michael M.; Jørgensen, Jes K.; Enoch, Melissa L.; Merín, Bruno; van Dishoeck, Ewine F.; Alcalá, Juan M.; Myers, Philip C.; Stapelfeldt, Karl R.; Huard, Tracy L.; and 8 coauthors	343.000 The Spitzer c2d Legacy Results: Star-Formation Rates and Efficiencies; Evolution and Lifetimes	04/2009	A E F X D R C S O U



Science Legacy

A true Legacy dataset

Many ancillary datasets with lasting significance



Science Legacy

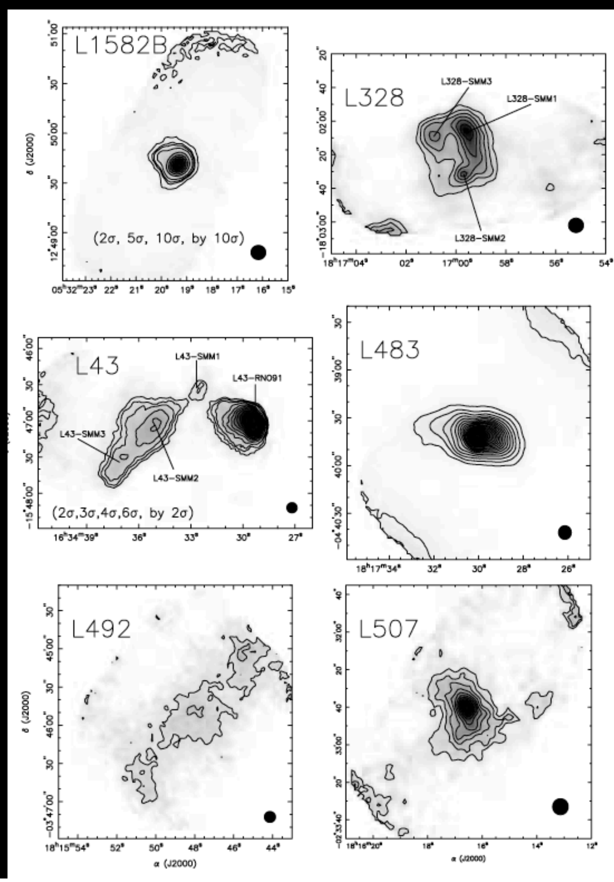
A true Legacy dataset

Many ancillary datasets with lasting significance

The Astronomical Journal, 133:1560–1584, 2007 April

SHARC-II MAPPING OF *SPITZER* c2d SMALL CLOUDS AND CORES

Jingwen Wu,[1] Michael M. Dunham,[1] Neal J. Evans II,[1] Tyler L. Bourke,[2] and Chadwick H. Young[3]
Received 2006 August 25; accepted 2006 December 11



The Astronomical Journal, 132:1998–2013, 2006 November

SUBMILLIMETER COMMON-USER BOLOMETER ARRAY MAPPING OF *SPITZER* c2d SMALL CLOUDS AND CORES

Chadwick H. Young
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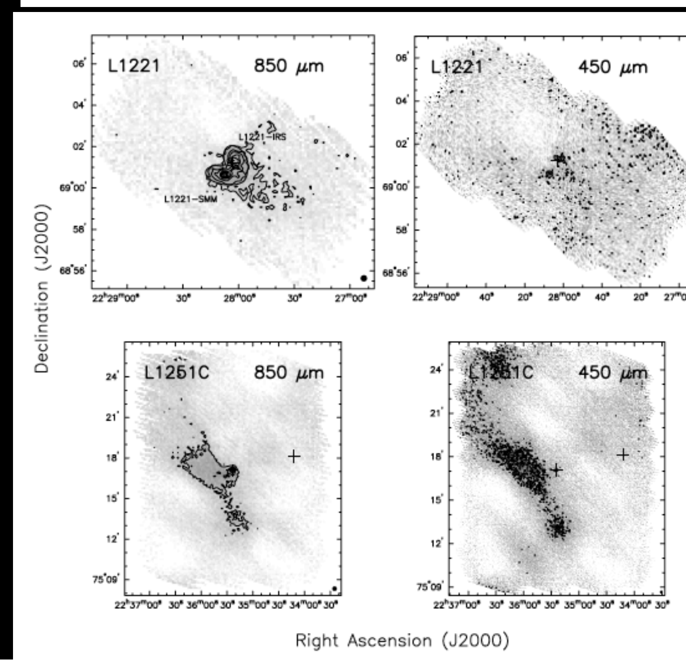
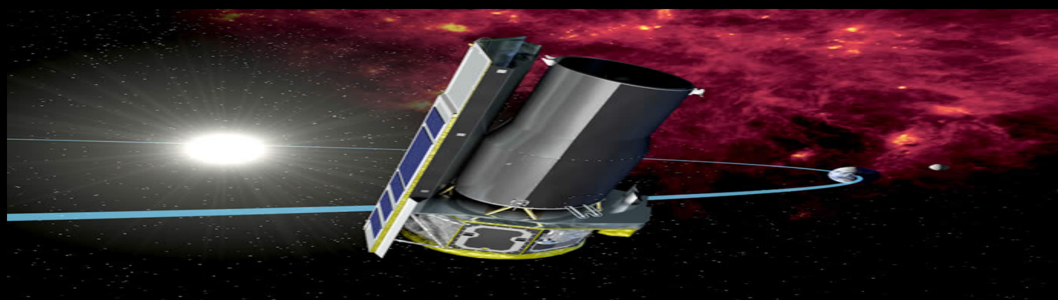
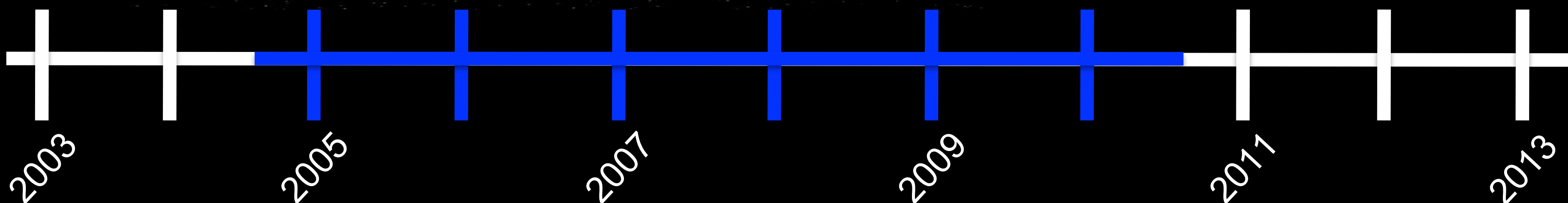
Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, Netherlands
Received 2006 May 16; accepted 2006 June 28



People Legacy

>10 PhDs





Many key steps in data processing and science analysis led by students

Excellent example of how to maximize productivity from a large team

Long-lasting personal and professional connections

Spitzer Legacy: From Cores to Disks

c2d

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