

(Galactic) Radio Astronomy in Chile: an historical perspective

**Leonardo Bronfman
Astronomy Department
Universidad de Chile**

Atacama: The driest desert in the world



Optical Astronomy Observatories in northern Chile; 1960s



1971 Las Campanas (CARSO)



1969 La Silla (ESO)

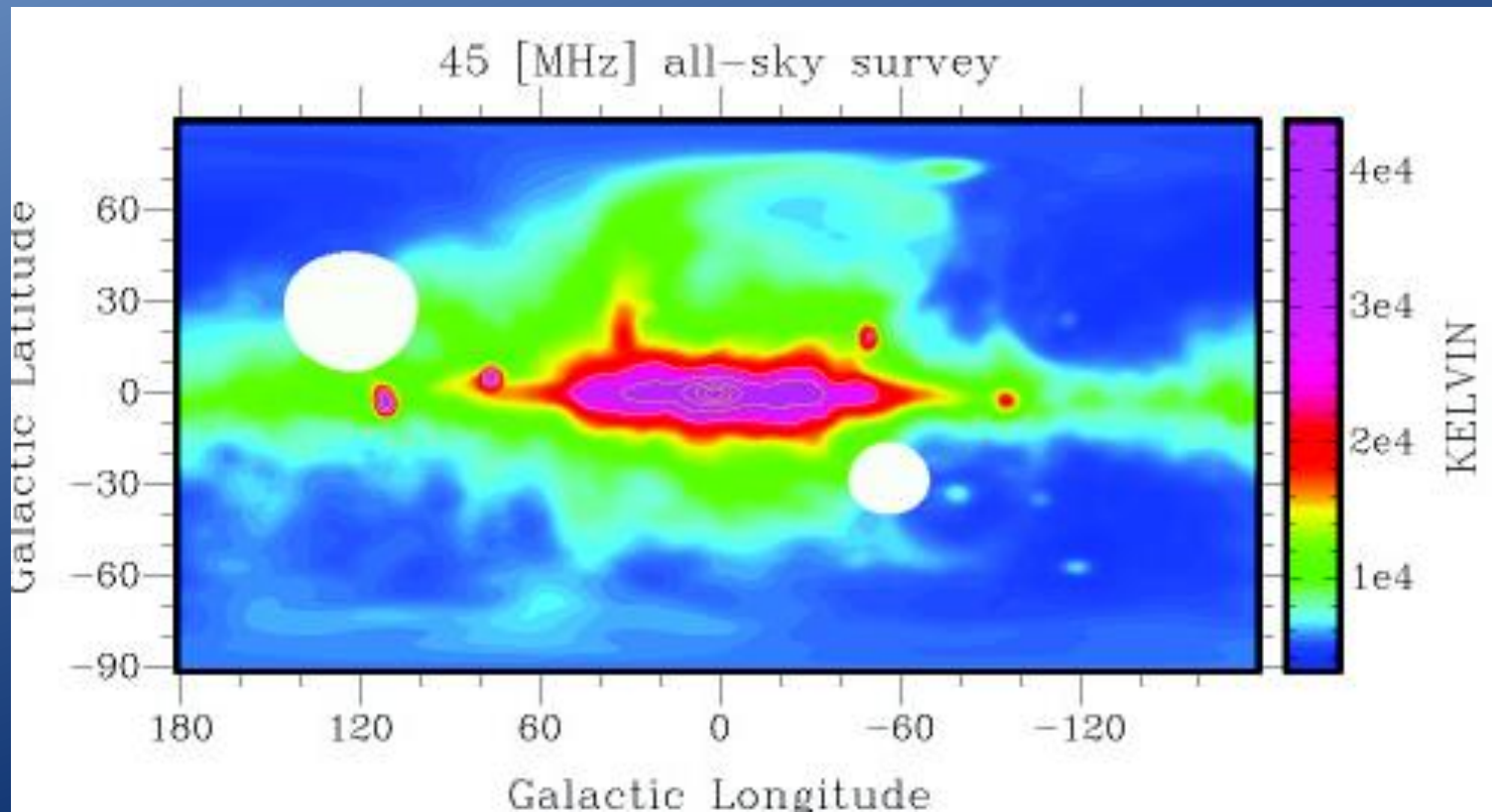


1966 Cerro Tololo (CTIO-NOAO)

Early radio astronomy in Chile : Maipú Observatory (1959-2000)
43-46 MHz; 528 dipoles in 10.000 m²; first in Latin America
Prof. Jorge May, Universidad de Chile (U. Florida)



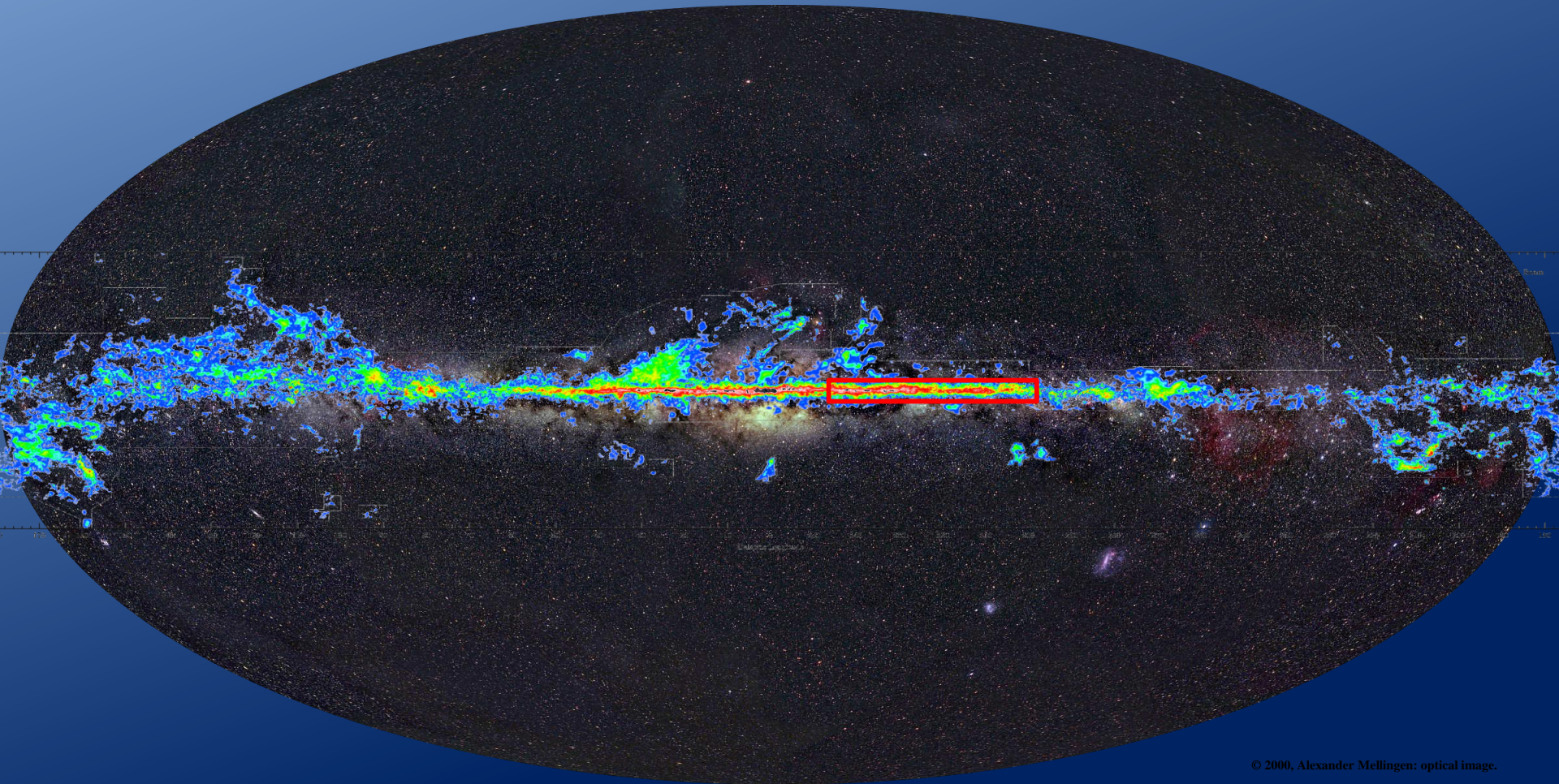
- First complete map of the full sky at 45 MHz
- Lowest frequency map available (U. Chile - U. Hyogo)



RADIO OBSERVATORIO DE MAIPU, NOVIEMBRE 1979



The Milky Way



© 2000, Alexander Mellinger: optical image.

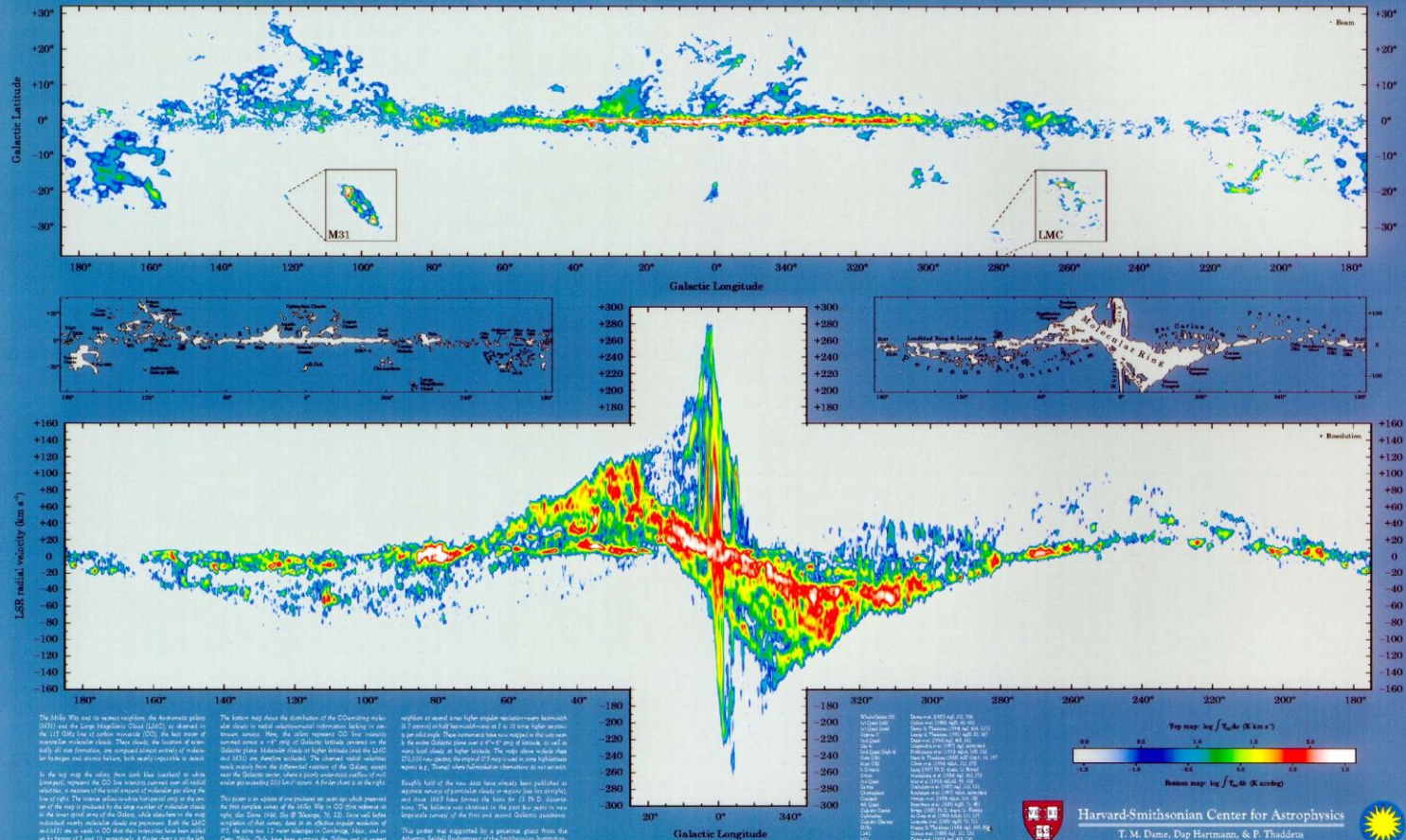
Dame et al. 2001: CO(1-0) image.

E.E.Barnard's dilemma (1900)
Holes in the heavens or obscuring matter?

(A.Eddington: "flying with one wing")

Molecular gas: CO survey of the Galaxy

The Milky Way in Molecular Clouds



The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), are situated in the 115 Gpc yr⁻¹ of carbon monoxide (CO), the best tracer of molecular molecular clouds. These clouds, the reservoir of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect in the top stage of the galaxy. Their study has revealed in which environments, wherever the CO has recently formed, are all kinds of molecular gas, or measures of the total amount of molecules per along the line of sight. The results will be published in the next issue of the journal *Science*, which also reports on the map of the Milky Way in CO, which also shows in the map individual nearby molecular clouds and processes. Both the LMC and M31 are visible in CO, but their emissions have been studied by means of 7 and 10, respectively. A further study is in the left column.

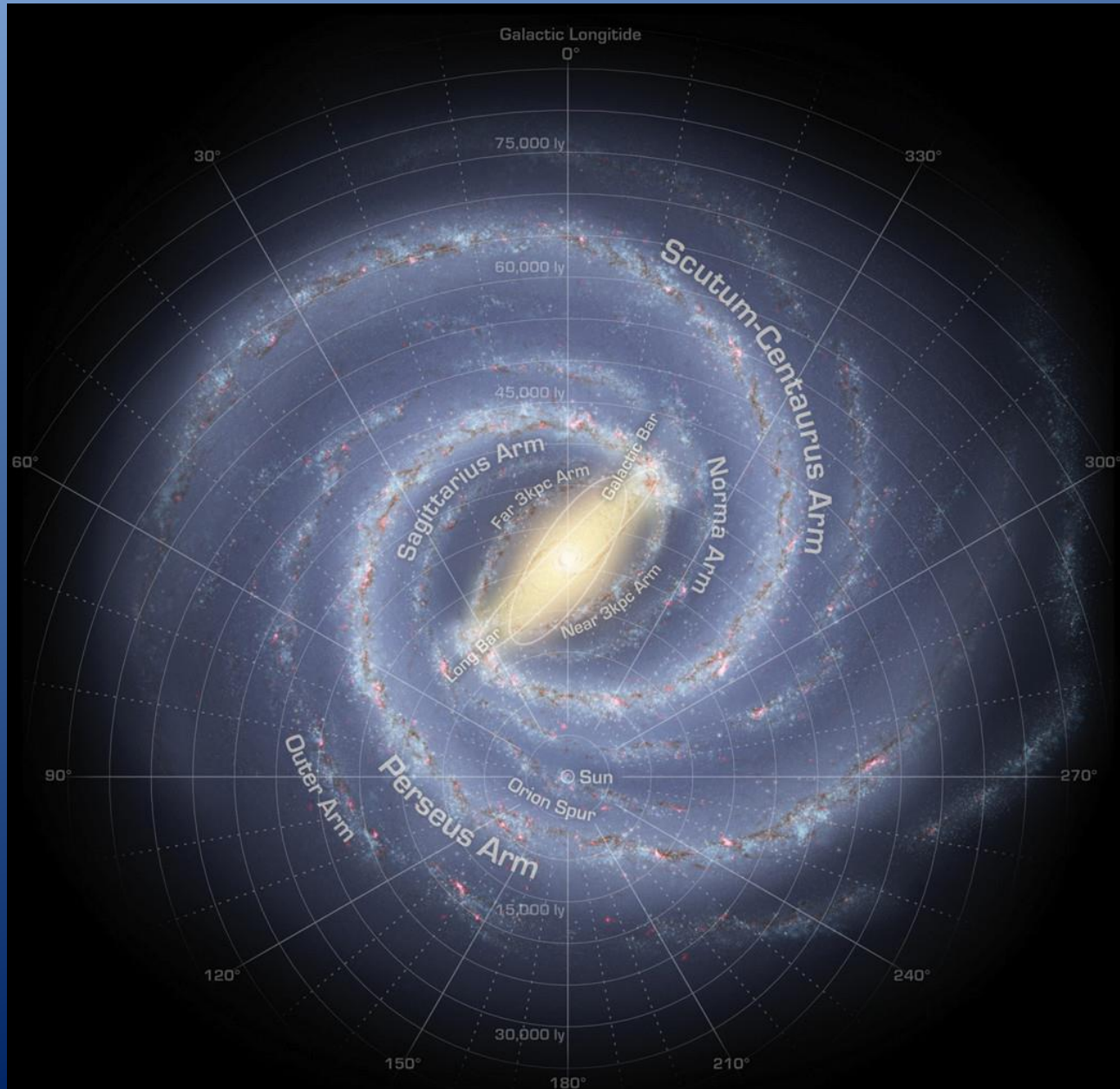
The bottom map shows the distribution of the CO survey results, which clearly in total unambiguously demonstrates the lack of molecular clouds. Here, the color represents CO, but mostly molecular gas, or CO, which is the best tracer of molecular gas in the Galaxy plane. Molecular clouds at higher latitudes (and the LMC and M31) are shown in white. The color scale indicates the LSR radial velocity, which is the difference between the Galactic rotation and the observed velocity of the clouds. The color scale indicates the LSR radial velocity, which is the difference between the Galactic rotation and the observed velocity of the clouds. The color scale indicates the LSR radial velocity, which is the difference between the Galactic rotation and the observed velocity of the clouds.

Results of the CO survey have already been published in major journals of particular clouds or regions (see list of references) and show that it has indeed the best (2.5 K) resolution. The latitude was obtained in the form of a map in the Galactic center of the first and second Galactic quadrants. This paper has supported by a generous grant from the Atlantic Seaboard Endowment of the Smithsonian Institution.

Observation ID	Observer	Observer	Observer
CO-1	CO-2	CO-3	CO-4
CO-5	CO-6	CO-7	CO-8
CO-9	CO-10	CO-11	CO-12
CO-13	CO-14	CO-15	CO-16
CO-17	CO-18	CO-19	CO-20
CO-21	CO-22	CO-23	CO-24
CO-25	CO-26	CO-27	CO-28
CO-29	CO-30	CO-31	CO-32
CO-33	CO-34	CO-35	CO-36
CO-37	CO-38	CO-39	CO-40
CO-41	CO-42	CO-43	CO-44
CO-45	CO-46	CO-47	CO-48
CO-49	CO-50	CO-51	CO-52
CO-53	CO-54	CO-55	CO-56
CO-57	CO-58	CO-59	CO-60
CO-61	CO-62	CO-63	CO-64
CO-65	CO-66	CO-67	CO-68
CO-69	CO-70	CO-71	CO-72
CO-73	CO-74	CO-75	CO-76
CO-77	CO-78	CO-79	CO-80
CO-81	CO-82	CO-83	CO-84
CO-85	CO-86	CO-87	CO-88
CO-89	CO-90	CO-91	CO-92
CO-93	CO-94	CO-95	CO-96
CO-97	CO-98	CO-99	CO-100

Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus

Face-on sketch view of the Galaxy obtained from optical, infrared, and mm data (Churchwell et al. 2009)

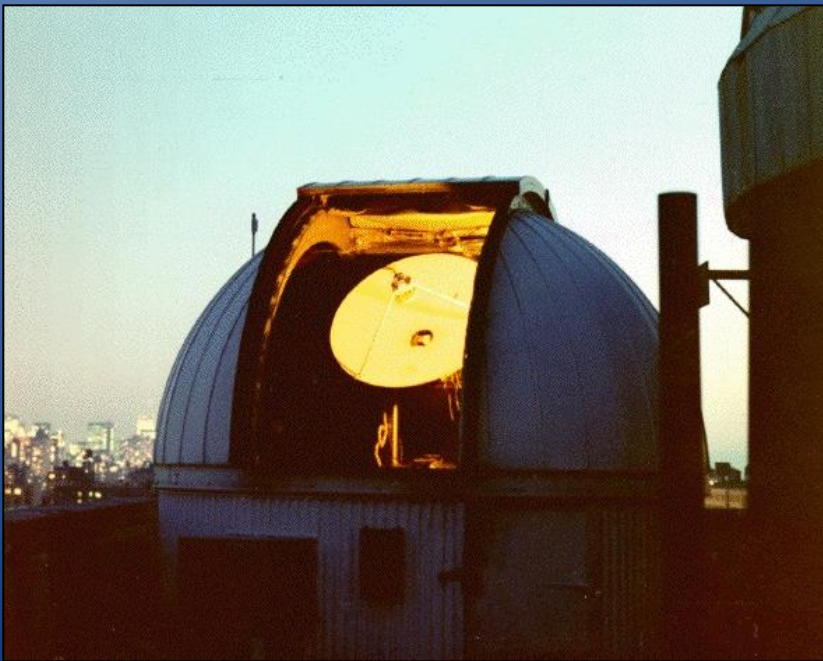


1.2m mm-wave Telescopes: Molecular Clouds in the Milky Way

Columbia University-Universidad de Chile

PI P. Thaddeus

- Twin telescopes built at Columbia University (1976-1982)
- Southern Mini to Cerro Tololo, Chile (1982)
- Northern Mini to CFA (1986)
- Resolution = $8''$ @ 115 GHz



NASA-Goddard, NY 1982
Southern mm-wave Telescope; first dedicated instrument in SH



1.2m Southern mm-Wave Telescope (Mini)

PINK FLOYD THE DIVISION BELL



CLUSTER ONE

WHAT DO YOU WANT FROM ME

POLES APART

MARDONED

A GREAT DAY FOR FREEDOM

WEARING THE INSIDE OUT

TAKE IT BACK

COMME BACK TO LIFE

KEEP TALKING

LOST FOR WORDS

HIGH HOPES

David Gilmore:
guitars, vocals, bass

keyboards and programming

Nick Mason:

drums and percussion

Richard Wright:

keyboards and vocals

Produced by

Bob Ezrin and David Gilmore

Mixed by

Chris Thomas and David Gilmore



CLUSTER ONE
Music: Wright/Gilmore

Jon Carin:
programming and additional keyboards

Guy Pratt:

bass

Gary Wallis:

played and programmed percussion

Tim Renwick:

guitars

Dick Parry:

tenor saxophone

Bob Ezrin:

keyboards and percussion

Backing Vocals:

Sam Brown, Durga McBroom, Carol Kenyon

Jackie Sheridan and Rebecca Leigh-White

Recording and mixing engineer:

Andrew Jackson

Orchestra arranged by

Michael Kamen

Orchestrations by

Michael Kamen and Edward Shearmur

Orchestra conducted by

Steve McLaughlin

Recorded at Astoria recording studio, London

Britannia Row recording studios

Abbey Road recording studios

Metropolis studios

The Coach recording studios, Tring, Herts

Mixing assisted by the TCSO monitoring system

Assistant engineer: W. G. Brown, Bob Brown

Illustrated by

Paul Stewart, Bill and Diana, Douglas, Albert

Anthony Brown, Norman Redding

TRES

Ara OB1: A stellar association formed by the action of an energetic event?

E.M. Arnal^{1,2,*}, J.C. Cersosimo^{1,**}, J. May³, and L. Bronfman^{3,4}

¹ Instituto Argentino de Radioastronomía, C.C. 5, 1894 Villa Elisa, Argentina

² Observatorio Astronómico La Plata, Universidad Nacional de La Plata, Av. Paseo del Bosque S/N, 1900 La Plata, Argentina

³ Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

⁴ Columbia University and Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

Received July 16, 1985; accepted February 14, 1986

Summary. Neutral hydrogen (at $\lambda = 21$ cm) and carbon monoxide (at $\lambda = 2.6$ mm) line observations of the interstellar medium in the neighbourhood of the association Ara OB1 are reported. The observed H I distribution indicates the presence of an expanding structure. The total H I mass associated with such feature amounts to 4800 solar masses, and its momentum and kinetic energy are $\sim 4 \cdot 10^4 M_{\odot} \text{ km s}^{-1}$ and $3 \cdot 10^{48}$ erg, respectively. The H I structure, 42 pc in diameter, expands at a speed of 10 km s^{-1} . A possible origin for the expanding H I structure, and a genetic link between such structure and Ara OB1 are proposed.

Key words: clusters: open, and associations – interstellar medium: bubbles – radio lines: 21-cm – stars: formation of

covers an area of roughly one square degree, its nucleus being the open cluster NGC 6193 ($l = 336^{\circ}7$; $b = -1^{\circ}6$). The low density ionized gas of the low surface brightness nebula RCW108, in which the association is embedded, was studied by Cersosimo (1982).

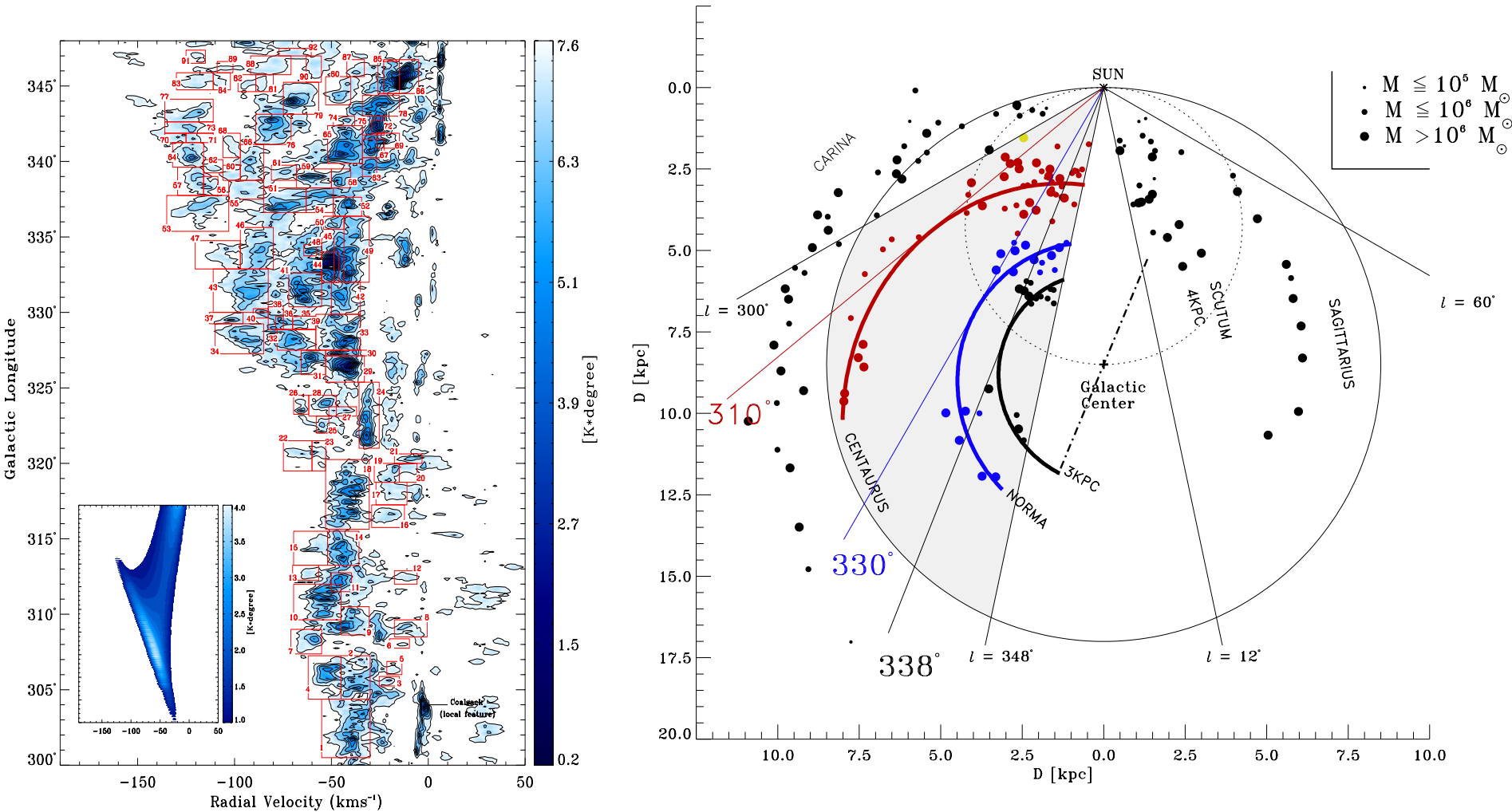
At almost two degrees northwest of the open cluster a spectroscopically peculiar Of star, HD 148937, is found. Such star is located within a large and nearly circular H II region, which is bounded by a thin dust shell (Westerlund, 1960). A physical interaction between the large H II region around HD 148937 and NGC 6193 was suggested by Bruhweiler et al. (1981).

Several signposts indicate that star-forming processes may still be going on in the area (Shaver and Goss (1970); Frogel and Persson (1974); Obscuring material, mainly identified as the dark clouds FS 332, FS 335 and FS 337 (Feitzinger and Stuwe, 1984), is

INDIVIDUAL CLOUD ANALYSIS:

THE CO EMISSION IS DOMINATED BY GMCs WHICH TRACE THE SPIRAL ARMS

P. García et al. 2013: new 4th quadrant analysis



STUDY CASE: G331.5 GMC in Norma Spiral Arm
Among most massive in the Galactic disk (1985)
Little distance ambiguity, close to arm tangent
HII Regions, SNRs

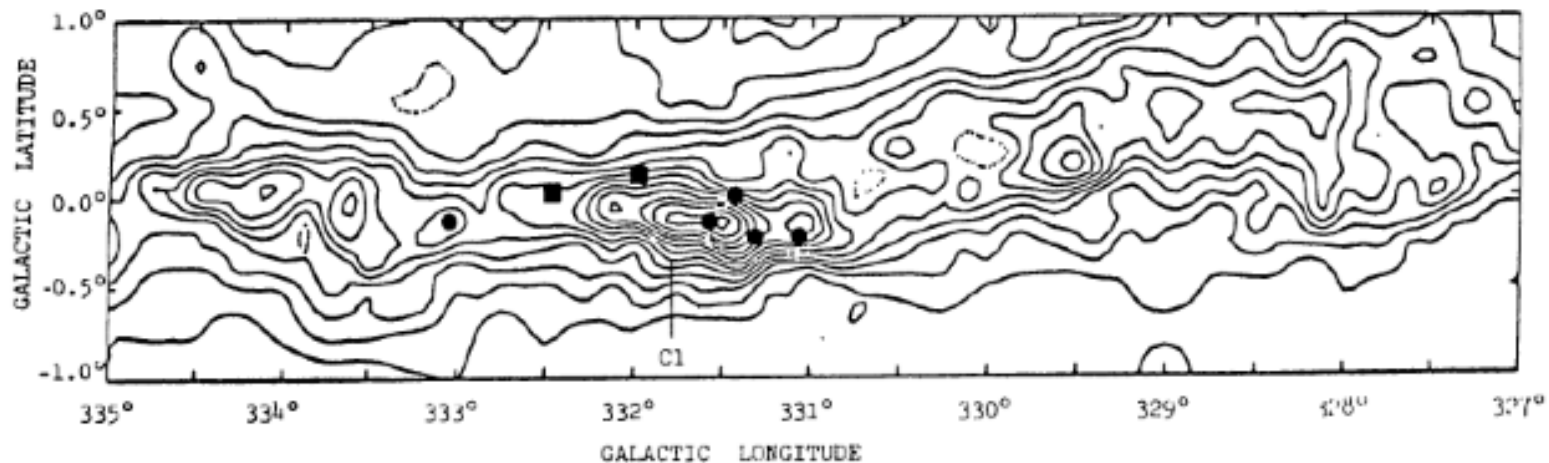


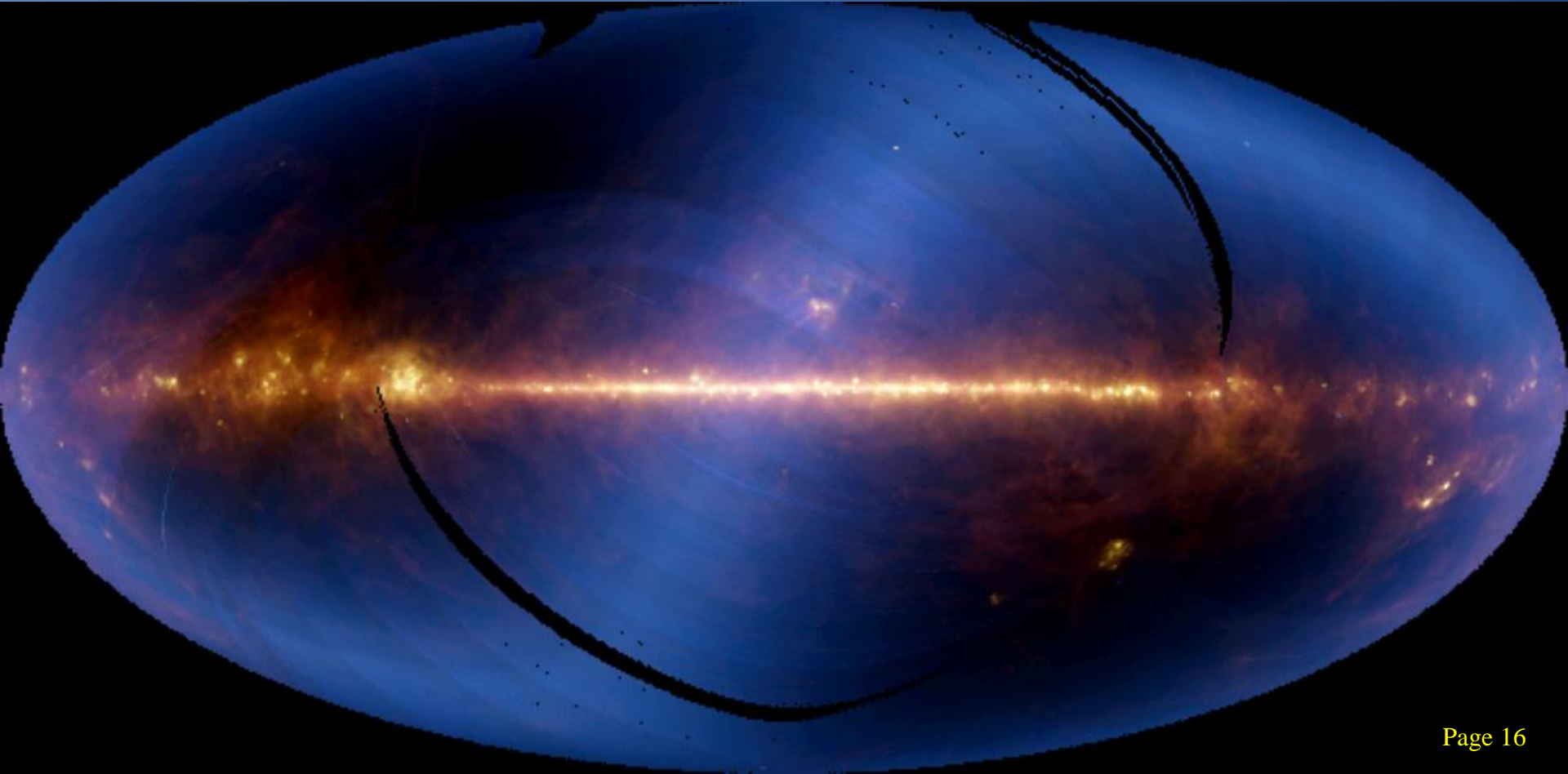
Figure 3. l, v map of CO emission integrated over the highest velocity range ($-120 < v < -80$ km/s). Complex 1, in the figure, has a kinematical (near) distance of about 7 kpc. HII regions in the area are shown as filled circles, and SNRs as filled squares.

IRAS
BLUE = 12 μm
GREEN = 60 μm
RED = 100 μm

IRAS: STAR FORMATION IN THE GALAXY:

**FAR INFRARED EMISSION FROM DUST HEATED BY MASSIVE STARS;
DUST ASSOCIATED WITH MOLECULAR GAS;**

FIR POINT SOURCES ASSOCIATED WITH HIGH DENSITY CLUMPS

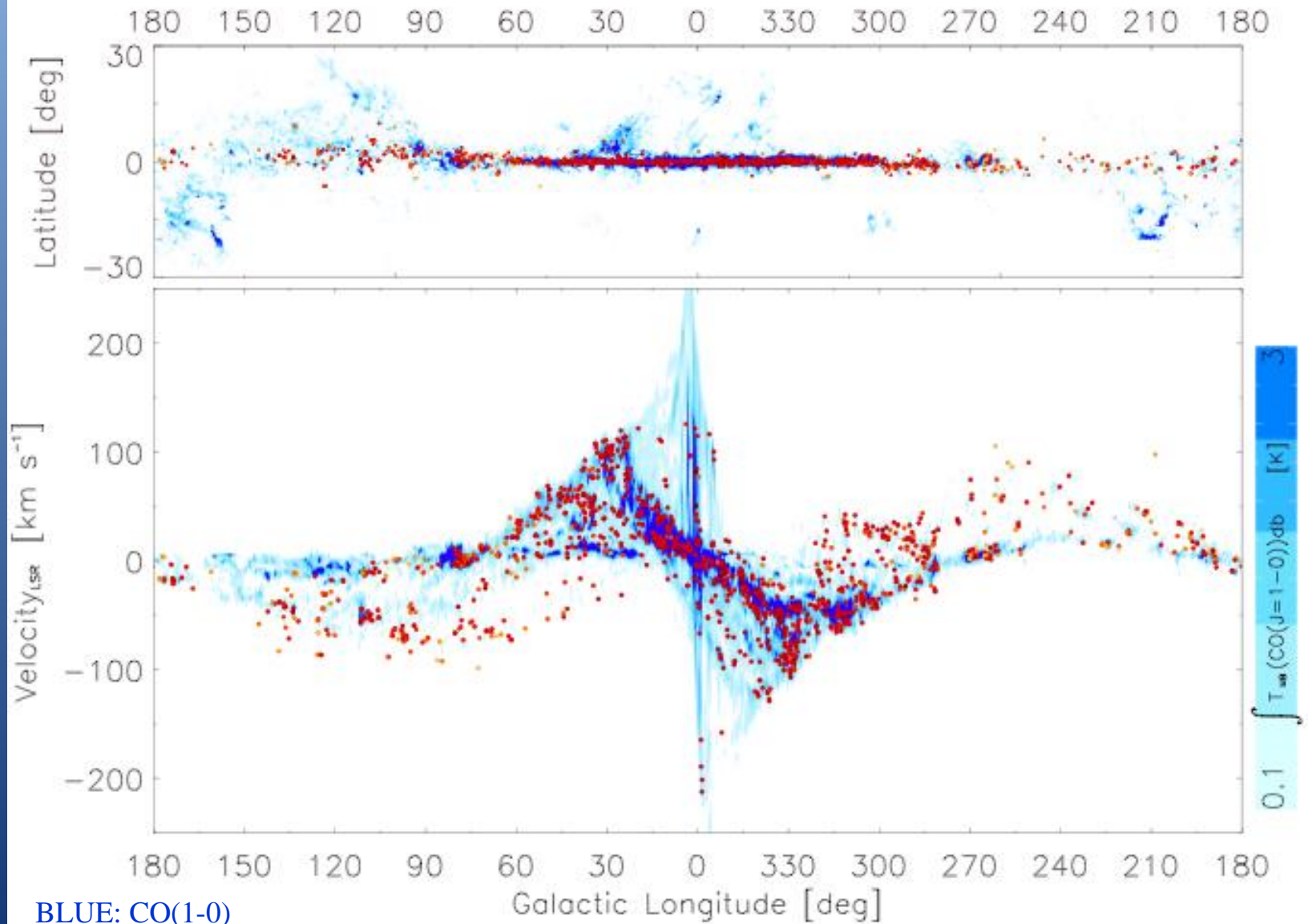


**SEST (Swedish ESO Sub-millimeter Telescope); La Silla Observatory, 1988 PI R. Booth
15m diameter antenna; 100 – 345 GHz frequency range; Res. = 45" @ 115 GHz**





THE MILKY WAY IN MOLECULAR CLOUDS AND YOUNG MASSIVE STARS



BLUE: CO(1-0)

RED: CS(2-1): 1200 UC H II REGIONS FROM IRAS PSC DETECTED WITH SEST AND ONSALA 20M

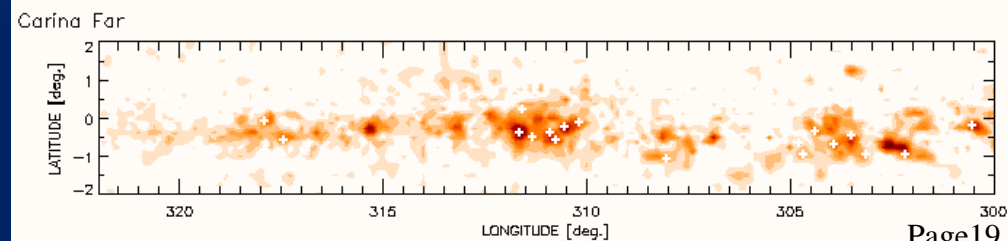
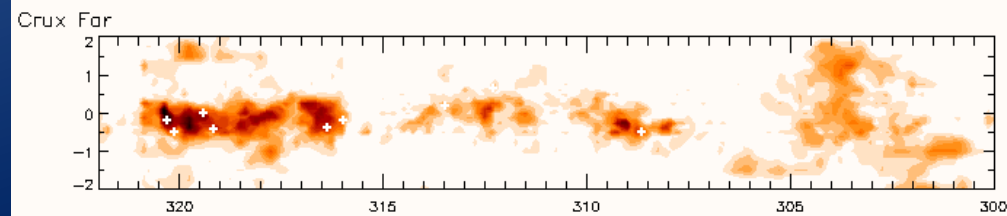
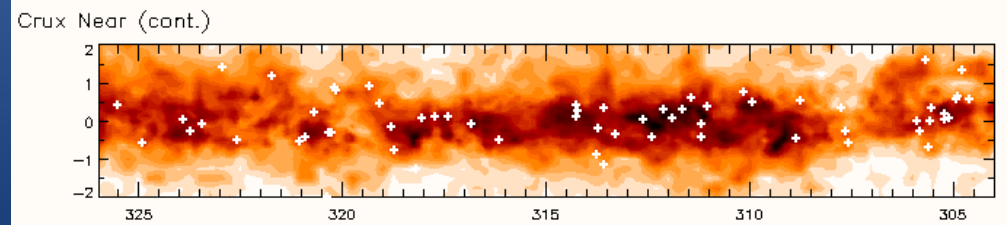
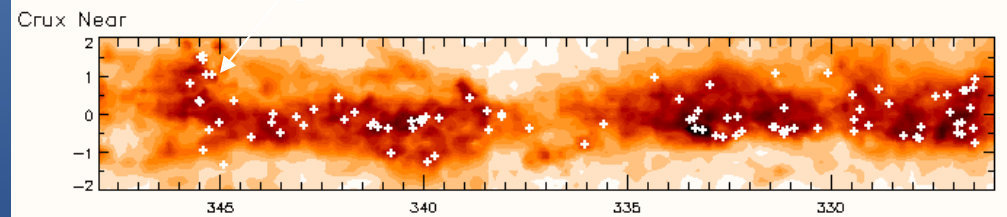
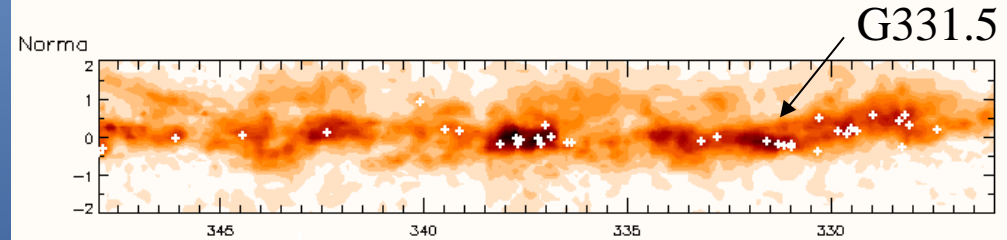
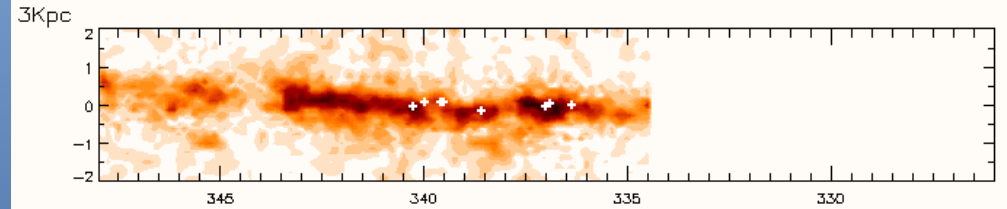
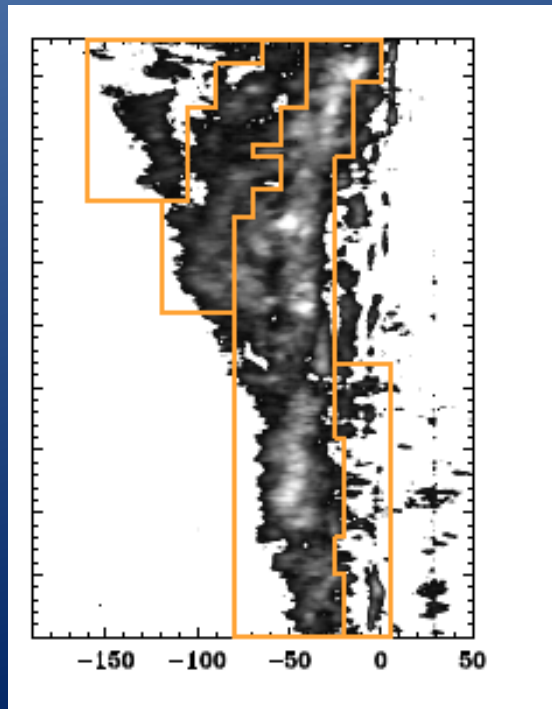


MASSIVE STARS FORM IN THE DENSE CORES OF GIANT MOLECULAR CLOUDS

COLOR: CO(1-0) INTEGRATED IN VELOCITY, WITHIN RANGES OF SPIRAL ARMS IN SOUTHERN GALAXY

CROSSES: MASSIVE STAR FORMING REGIONS DETECTED IN CS(2-1) (SEST)

NORMA G331.5:
D = 7.4 KPC IN TANGENT OF NORMA SPIRAL ARM.



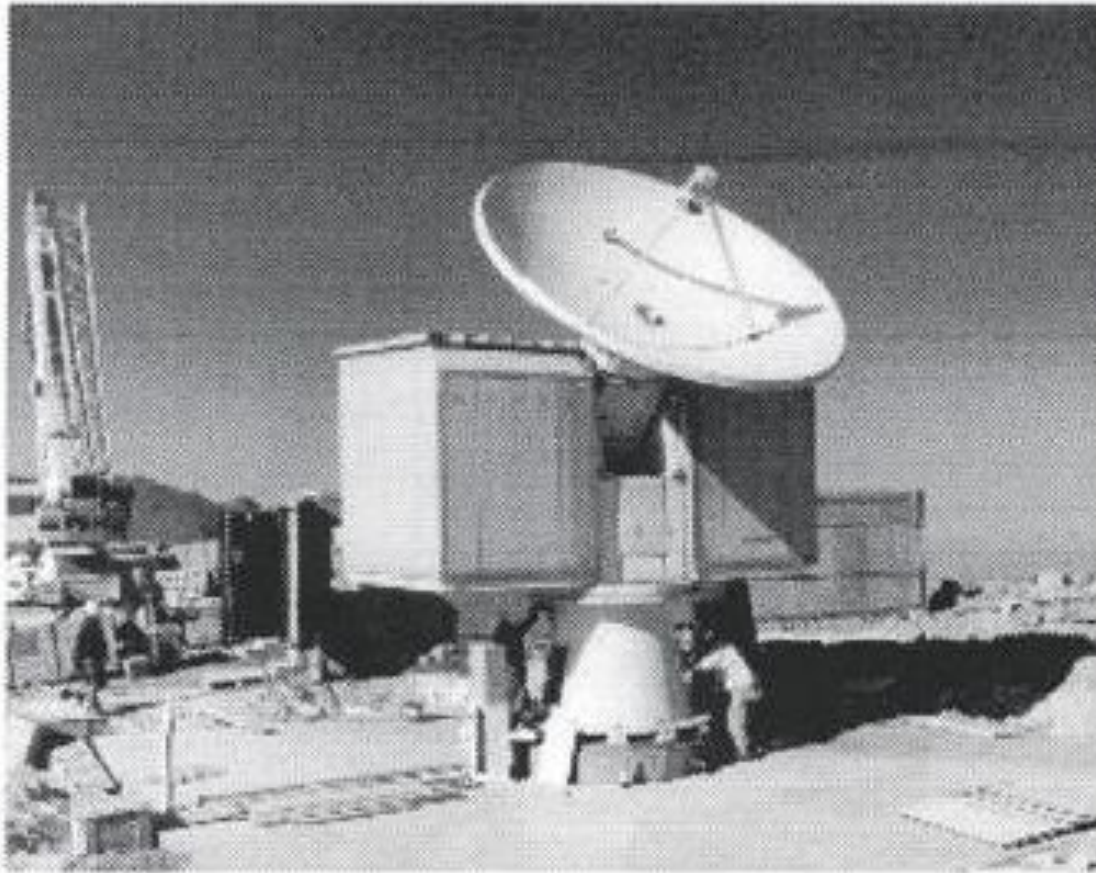
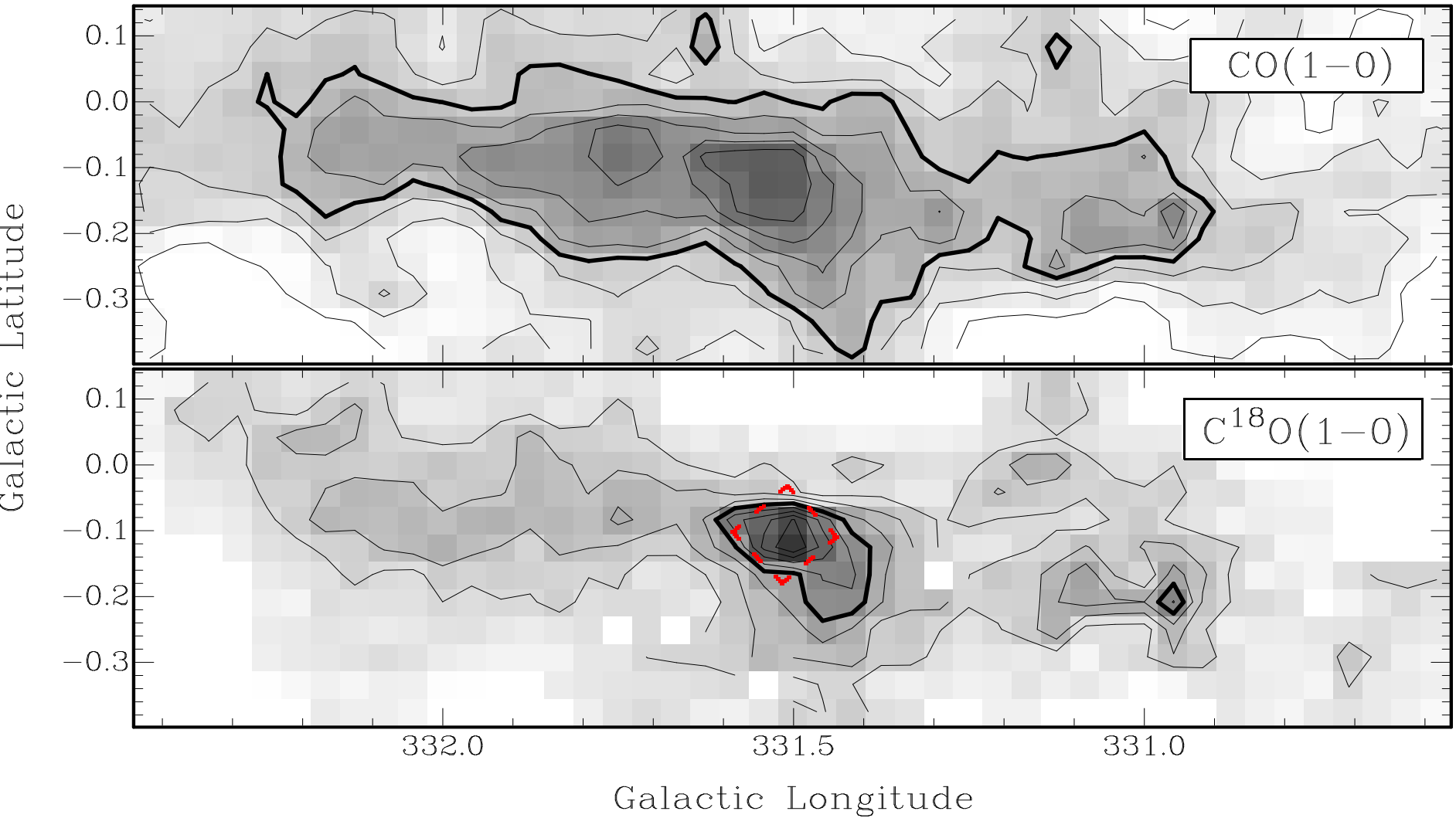


Figure 2. The 4-meter millimeter-wave telescope named NANTEN (=southern sky in Japanese) installed at Las Campanas Observatory in Chile.

Nagoya University NANTEN Telescope (Y. Fukui, 1995)
86 – 230 GHz coverage, 4m antenna, Las Campanas Observatory

NANTEN MAP OF NORMA G331.5; RESOLUTION 2.5 arcmin 3.5 MILLION SOLAR MASSES



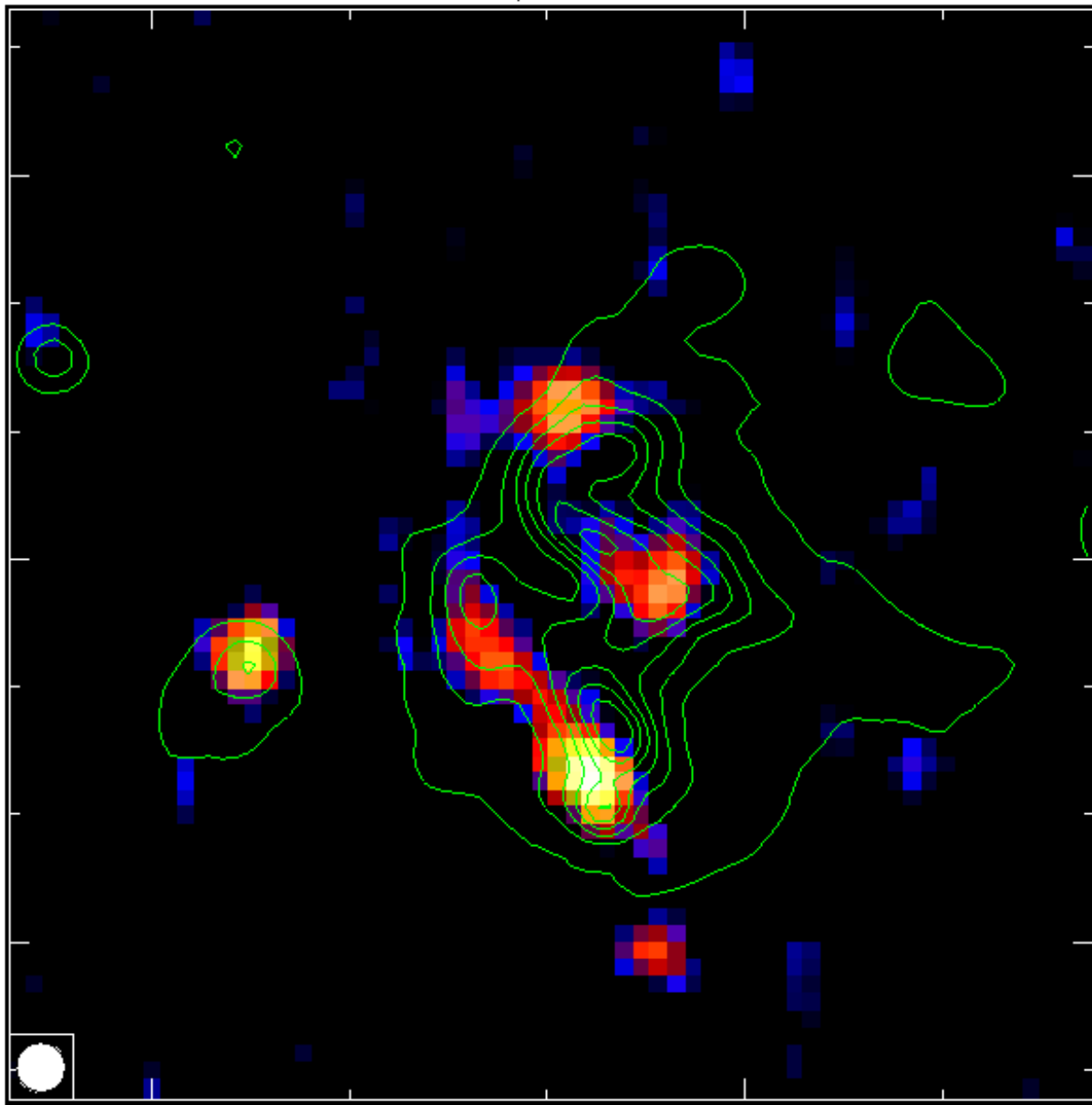
Norma region

Image: SIMBA at $\lambda = 1200 \mu\text{m}$

Contours: MSX at $\lambda = 8.3 \mu\text{m}$

Dec. (J2000)

-51°24'00"
-51°27'00"
-51°30'00"



16^h12^m30^s.0

16^h12^m00^s.0

R.A. (J2000)

ZOOMING IN THE DUST WITH SEST

SIMBA BOLOMETER (2001)

G331.5 MOLECULAR CLOUD CORE:

CONTINUUM EMISSION FROM DUST HEATED BY FORMING STARS

IN THE MEANTIME: THE ALMA SITE AT 5000 m, ATACAMA, CHILE (1994)



GENERAL VIEW OF PAMPA CHAJNANTOR

70 km from San Pedro town; 170 km from Calama, major mining city



Site survey expedition for NAOJ LMSA (pre ALMA); 1994



ALMA Site in Chile

NRAO & NAOJ test interferometers (1995-1996)



UNIVERSIDAD DE CHILE OBTAINED FIRST PERMIT FOR LAND SCIENCE USE



1st Instrument at the ALMA Site: CalTech Cosmic Background Imager (CBI 1999; PI Tony Readhead)

Observations of the polarized microwave background with microkelvin sensitivity.
Galactic microwave foreground.

- First generation of Chilean engineers in mm-wave instrumentation trained at CBI.
- Test of astronomical operations at the site.

Atacama Submillimeter Telescope Experiment (Japan ASTE 10 m Telescope, NAOJ , 2004) Present day frequency range up to 800 GHz



TRANSPORT OF ASTE
TO PAMPA LA BOLA AT
4850 M , CHILE ,
MARCH 2002
(S. SAKAMOTO)



NANTEN II Telescope from Las Campanas to Pampa La Bola, ALMA Site (2005).
New site allows observations up to 810 GHz (2005)



**Atacama Pathfinder
Experiment (APEX
12 m Telescope)**

**Chajnantor (ALMA
site, Chile, 5.050 m)**

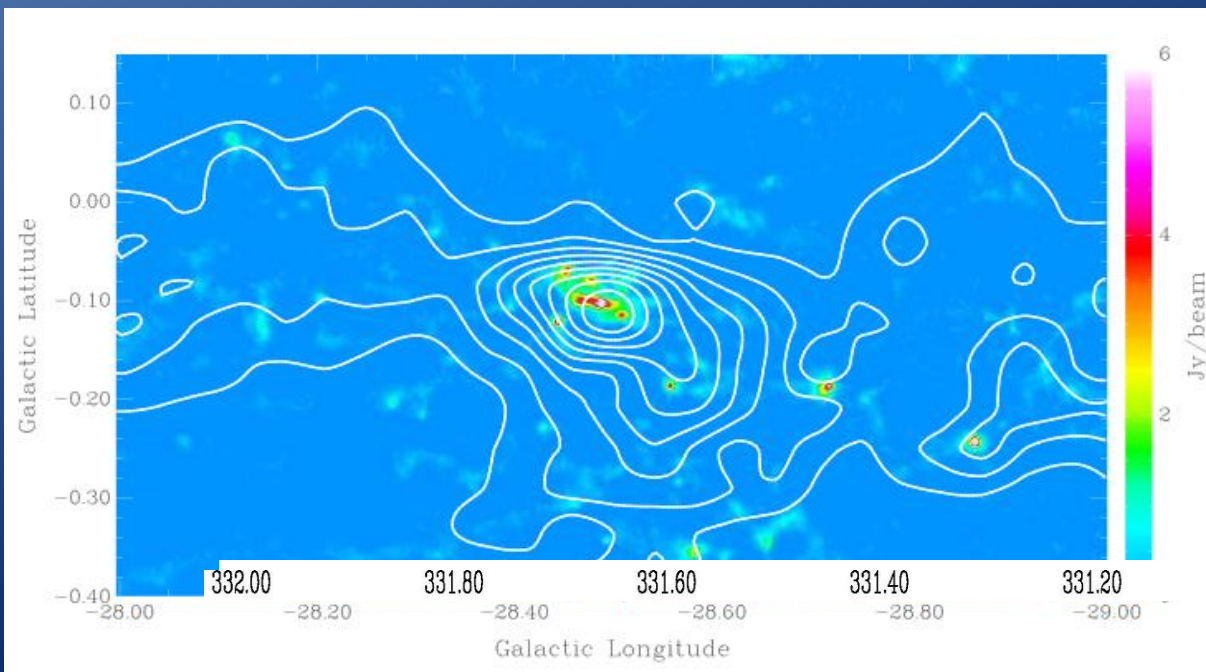
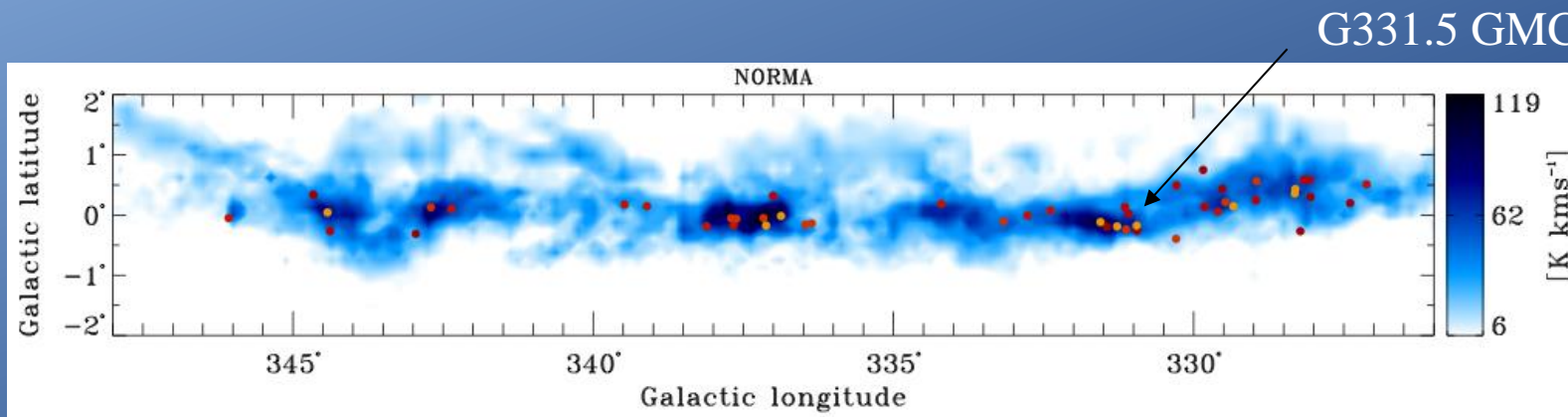
**MPIfR (K. Menten),
ESO, Onsala (2005)**

230 Ghz to 1 THz



Back to Astronomy:

The G331.5 GMC/Massive Star Forming Region in Norma; APEX LABOCA camera at 0.87 mm



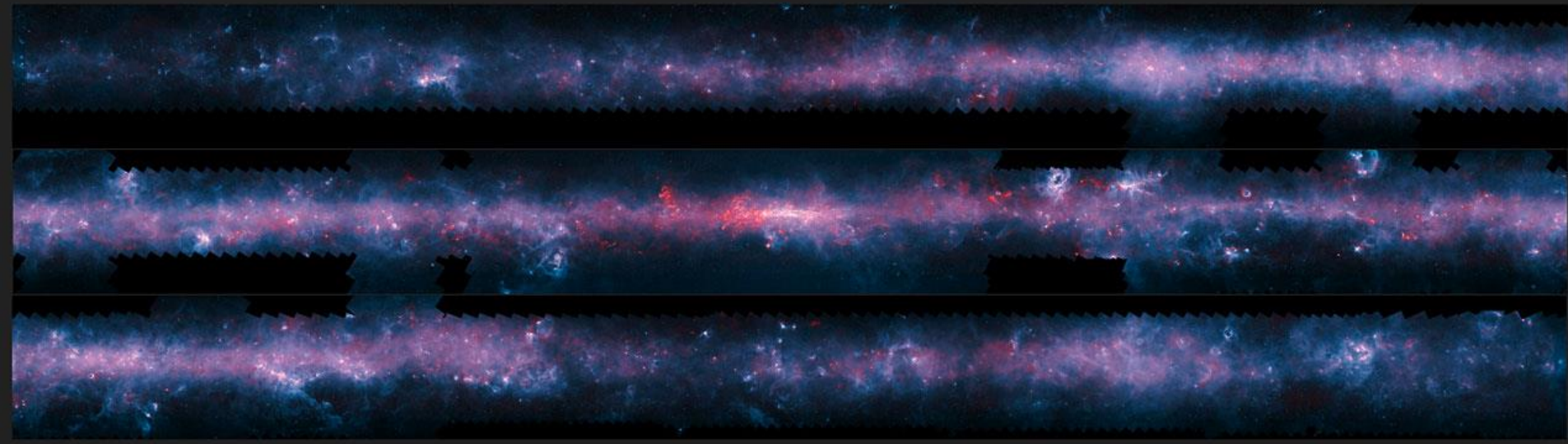
• Distance: 7.4 kpc

• FIR luminosity:
 $3.6 \times 10^6 L_{\odot}$

• Contours: NANTEN
 C^{18}O GMC mass: $3.5 \times 10^6 M_{\odot}$

• Color: APEX/LABOCA
0.87 mm dust continuum
emission

THE ATLASGAL SURVEY OF THE SOUTHERN GALAXY AT 0.87 mm (APEX-LABOCA) Csengeri et al 2016

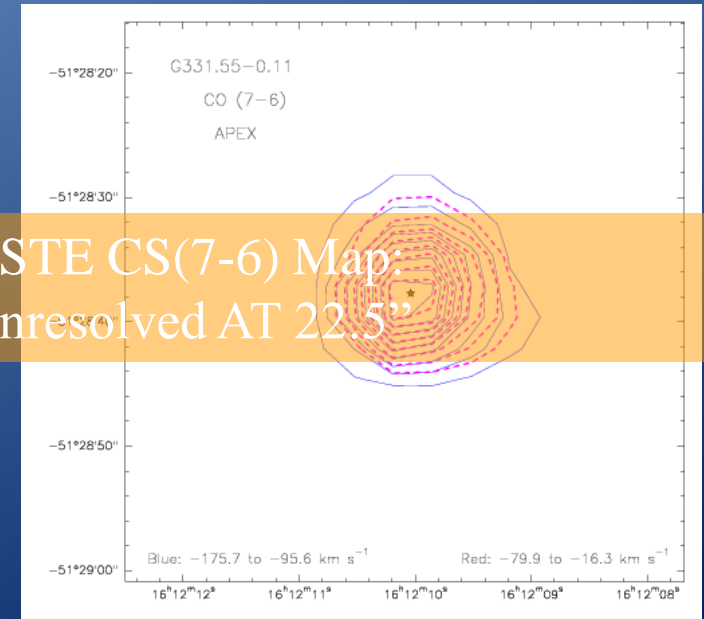
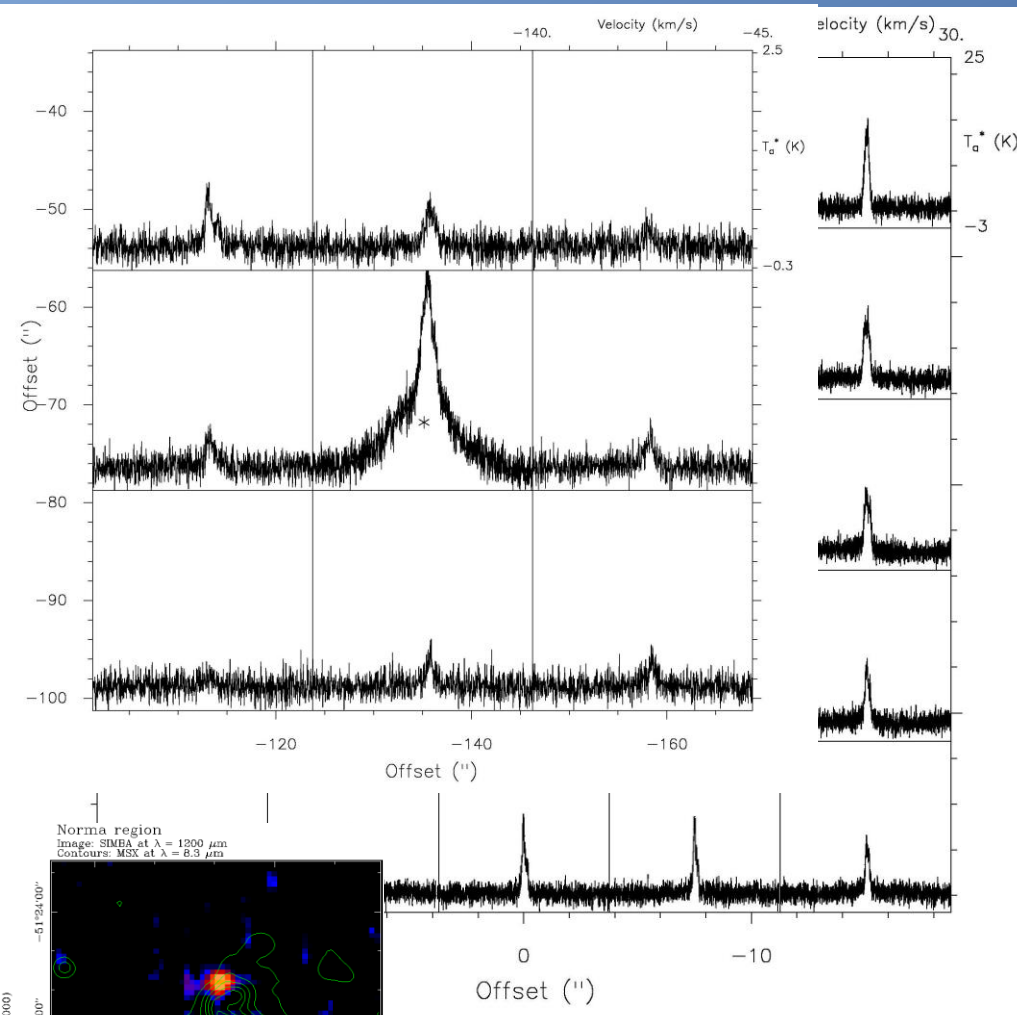


Red: ATLASGAL 0.87 mm

Blue: Spitzer/Glimpse 3.6-8 microns

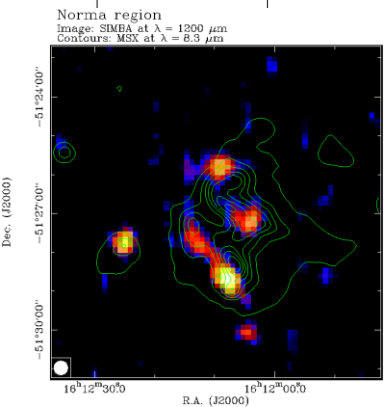
Extended Red: Planck data

Discovery of a massive molecular outflow in G331.5-0.1



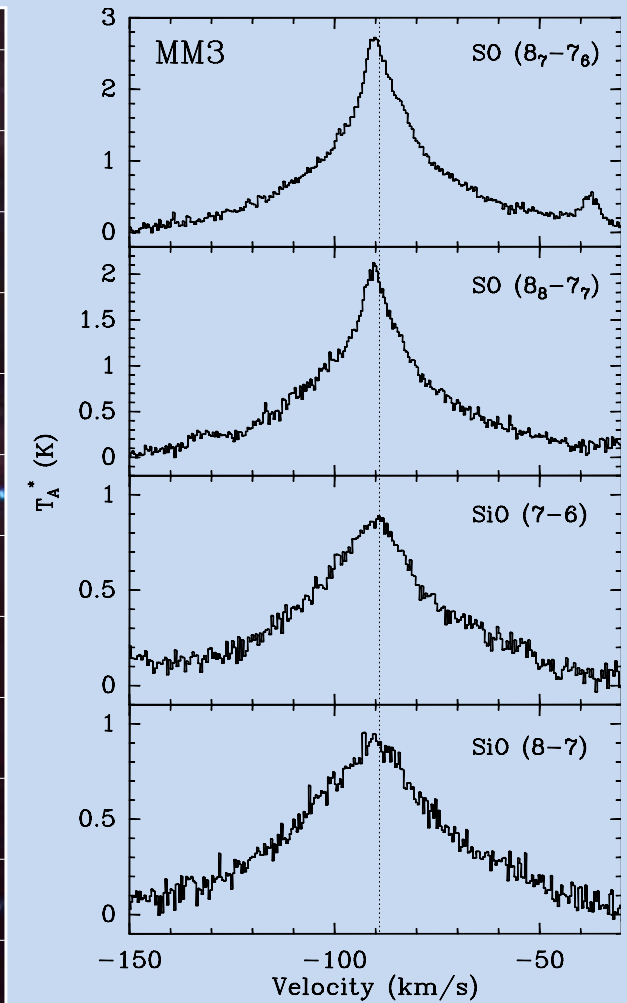
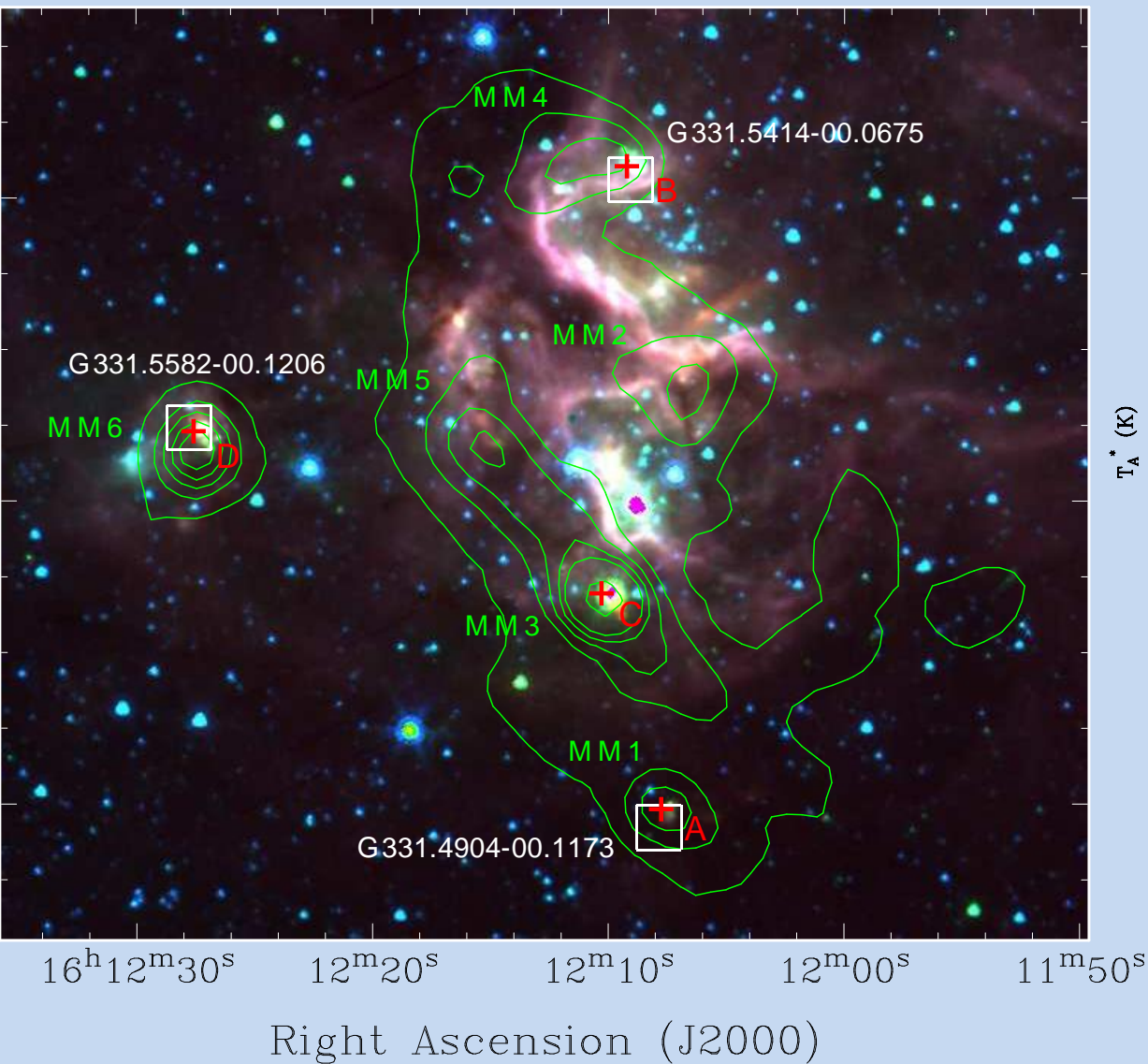
ASTE CS(7-6) Map:
Unresolved AT 22.5''

- APEX CO (7-6): Res 7.7''
- Velocity width (ZP) 160 km/s
- Dynamic timescale: less than 3×10^3 yrs.



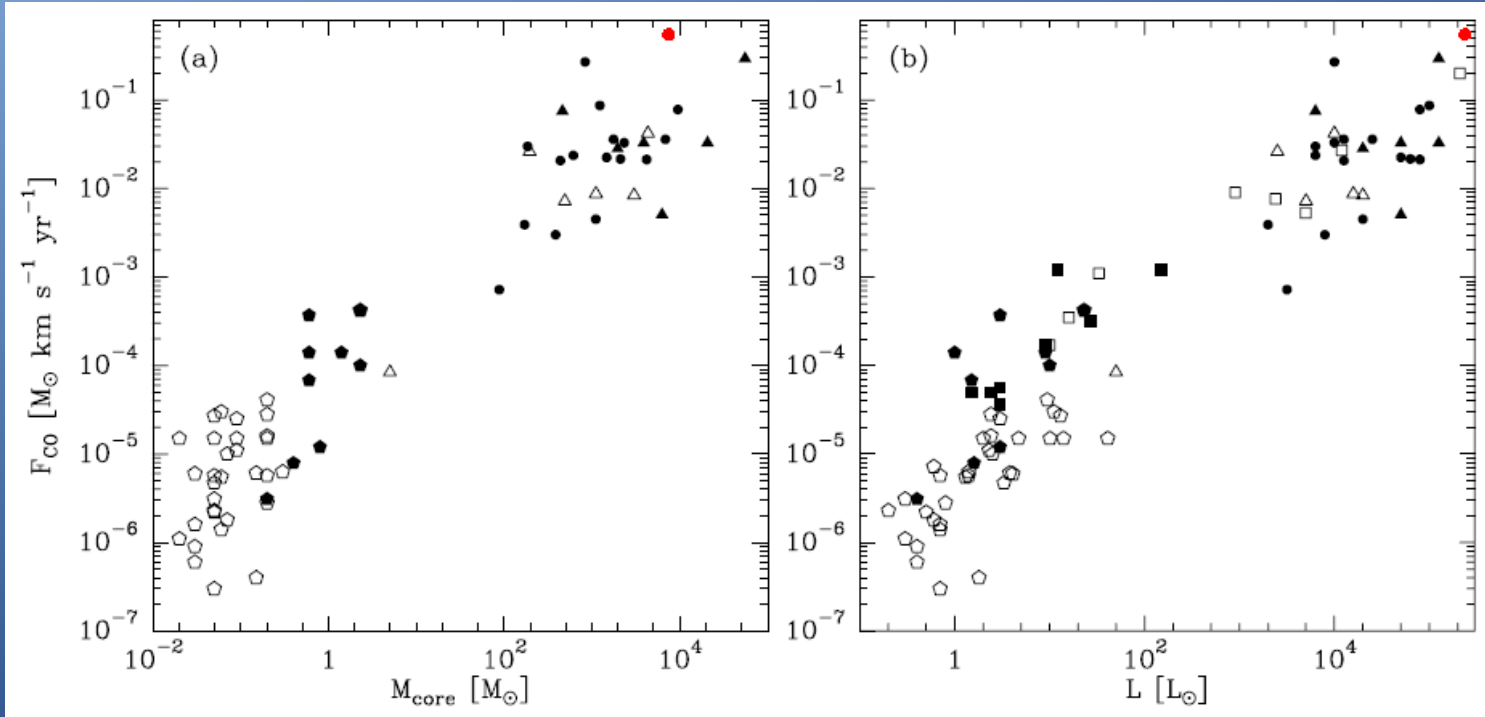
Contours: APEX-LABOCA 0.87 mm continuum
Colors: SPITZER-IRAC mid infrared

APEX spectra of shocked gas in
clump MM3; High velocity
molecular outflow G331.512-0.103



Mass and momentum loss rate

Beuther et al.,
2002b



Mass loss rate:

$$\dot{M}_w \sim 3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$$

High mass loss rate consistent with source luminosity $\sim 10^6 L_{\odot}$.

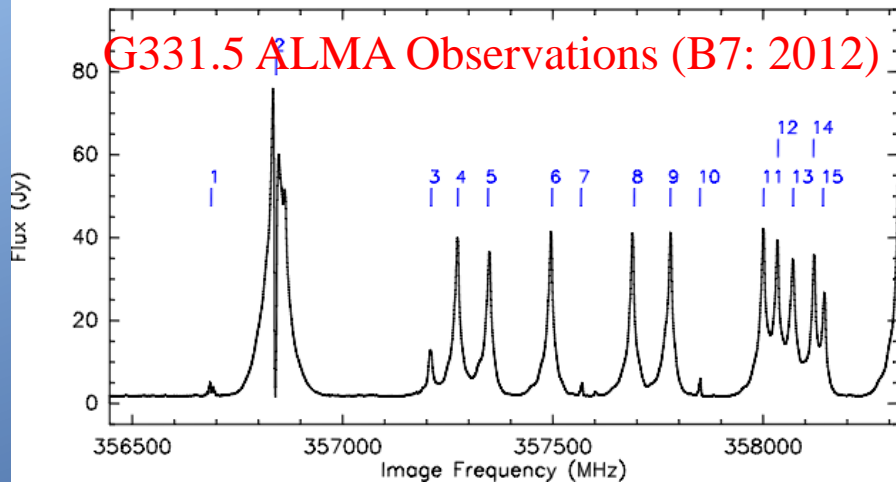
Spectral index of 1.1 between 4.8 and 8.6 GHz : free-free emission from thermal jet.

The ALMA Telescope: Science operations in 2012;
Largest (sub)mm-wave telescope in the world;
66 antennas: 54x12m + 12x7m, 35 to 950 GHz;
North America, Europe, East Asia; collaboration with Chile



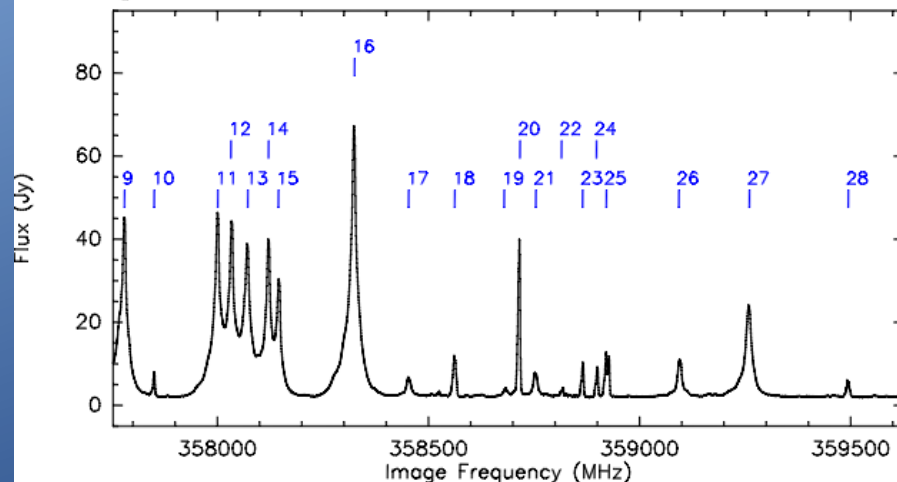
SPW0

G331.5 ALMA Observations (B7: 2012)



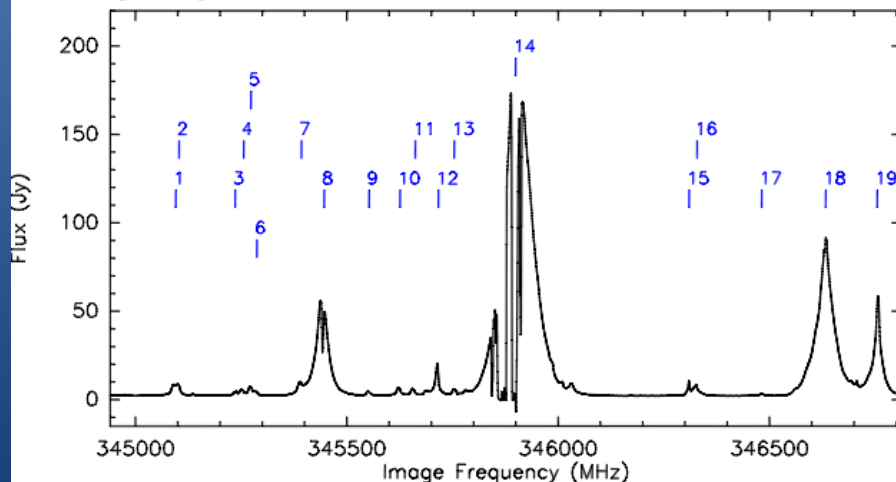
- 1 CH₃OCH₃ 8(4,5)-7(3,4)
- 2 HCO⁺ v=0 4-3
- 3 34SO₂ v=0 20(0,20)-19(1,19)
- 4 SO₂ v=0 13(4,10)-13(3,11)
- 5 SO₂ v=0 15(4,12)-15(3,13)
- 6 SO₂ v=0 11(4,8)-11(3,9)
- 7 CH₃OCH₃ 18(2,17)-17(1,16)
- 8 SO₂ V=0 8(4,4)-8(3,5)
- 9 SO₂ v=0 9(4,6)-9(3,7)
- 10 Unidentified
- 11 SO₂ v=0 7(4,4)-7(3,5)
- 12 SO₂ v=0 6(4,2)-6(3,3)
- 13 SO₂ v=0 17(4,14)-17(3,15)
- 14 SO₂ v=0 5(4,2)-5(3,3)
- 15 SO₂ v=0 4(4,0)-4(3,1)
- 16 SO₂ v=0 20(0,20)-19(1,19)
- 17 34SO₂ v=0 23(4,20)-23(3,21)
- 18 Unidentified
- 19 CH₃OCHO v=0 29(12,18)-28(12,17)A
- 20 CH₃OH v t=0 4(1,3)-3(0,3)
- 21 S18O 9(9)-8(8)

SPW1



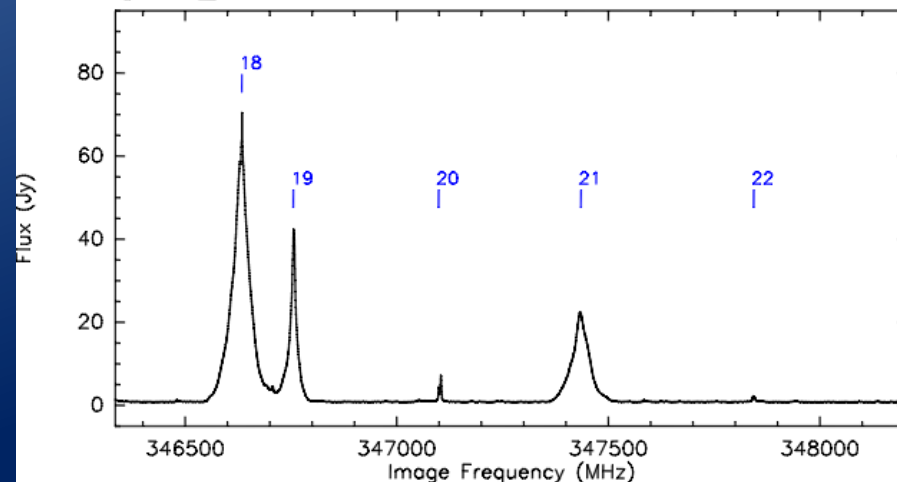
- 9 CH₃OCH₃ 18(2,17)-17(1,16)
- 10 Unidentified
- 11 SO₂ v=0 7(4,4)-7(3,5)
- 12 SO₂ v=0 6(4,2)-6(3,3)
- 13 SO₂ v=0 17(4,14)-17(3,15)
- 14 SO₂ v=0 5(4,2)-5(3,3)
- 15 SO₂ v=0 4(4,0)-4(3,1)
- 16 SO₂ v=0 20(0,20)-19(1,19)
- 17 34SO₂ v=0 23(4,20)-23(3,21)
- 18 Unidentified
- 19 CH₃OCHO v=0 29(12,18)-28(12,17)A
- 20 CH₃OH v t=0 4(1,3)-3(0,3)
- 21 S18O 9(9)-8(8)
- 22 Unidentified
- 23 CH₃CCH v=0 21(3)-20(3)
- 24 CH₃CCH v=0 21(2)-20(2)
- 25 CH₃CCH v=0 21(1)-20(1) / CH₃CCH v=0 21(0)-20(0)
- 26 Unidentified (possible 34SO₂ v=0 15(2,14)-14(1,13))
- 27 SO₂ v=0 25(3,23)-25(2,24)
- 28 CH₃OCH₃ 12(3,10)-11(2,9)

SPW3



- 1 34SO₂ v=0 15(4,12)-15(3,13)
- 2 34SO₂ v=0 11(4,8)-11(3,9)
- 3 CH₃OCH₃ 35(2,33)-35(1,34)
- 4 Possible SO₂ v=0 5(5,1)-6(4,2)
- 5 34SO₂ v=0 8(4,4)-8(3,5)
- 6 NH₂CHO 17(0,17)-16(0,16)
- 7 Unidentified (possible 34SO₂ v=0 9(4,6)-9(3,7))
- 8 H13CN v=0 J=4-3
- 9 SO₂ v=0 26(9,17)-27(8,20)
- 10 34SO₂ v=0 7(4,4)-7(3,5)
- 11 34SO₂ v=0 6(4,2)-6(3,3)
- 12 HC₃N v=0 J=38-37
- 13 34SO₂ v=0 6(4,2)-6(3,3)
- 14 CO v=0 3-2
- 15 CH₃OH v t=0 5(4,2)-6(3,3)-- / CH₃OH v t=0 5(4,1)-6(3,4)++
- 16 NS J=15/2-13/2, Omega=1/2, F=17/2-15/2, I=f

SPW2



- 17 SO₂ v=1 19(1,19)-18(0,18)
- 18 SO₂ v=0 16(4,12)-16(3,13)
- 19 SO₂ v=0 19(1,19)-18(0,18)
- 20 H13CO⁺ 4-3
- 21 SiO v=0 8-7
- 22 SO⁺ J=15/2-13/2, Omega=1/2, I=e

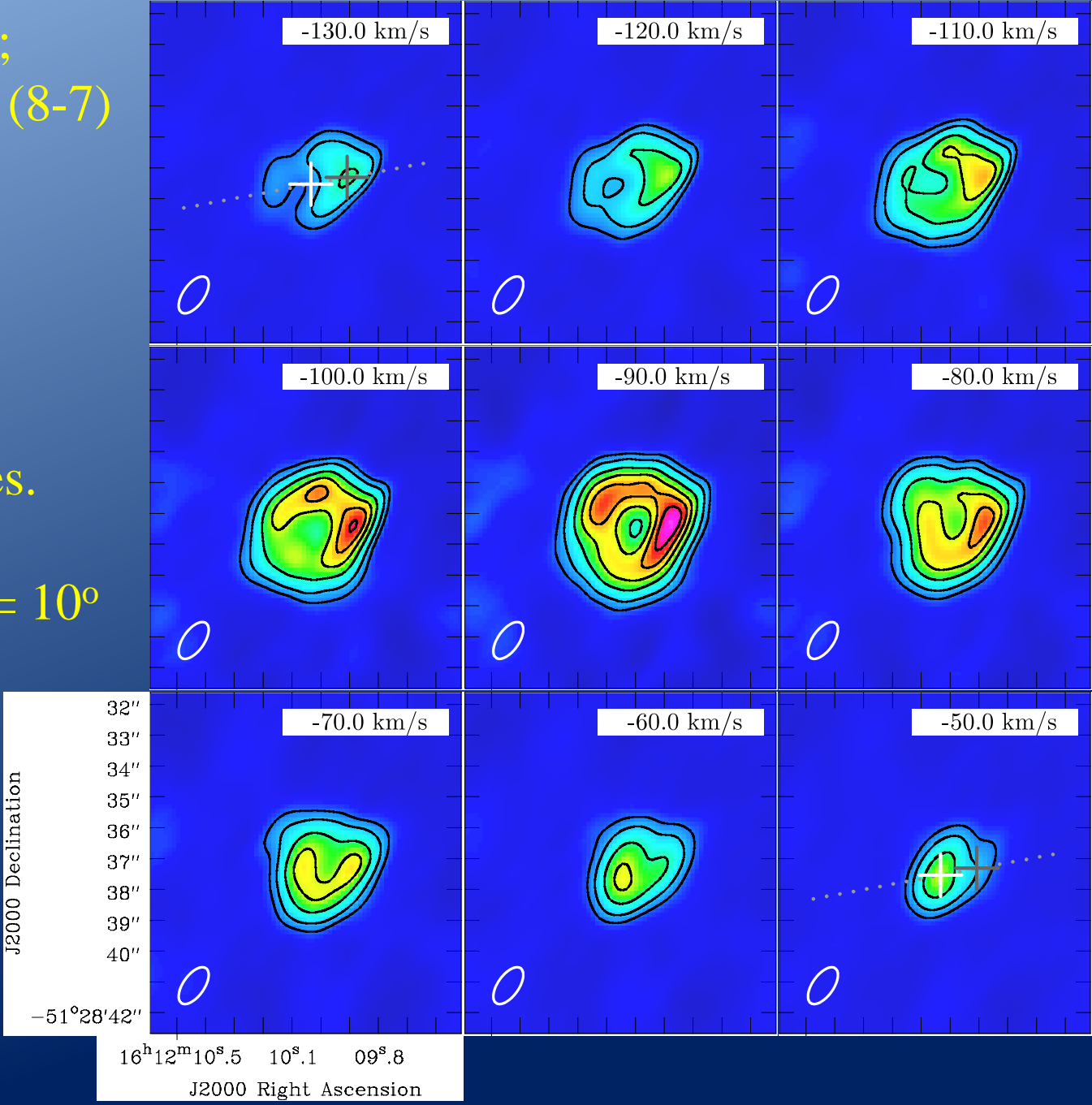
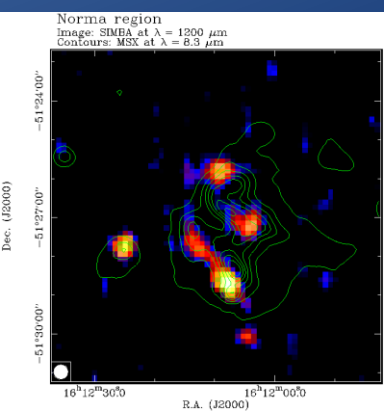
*G331.5 with ALMA;
Channel maps of SiO (8-7)

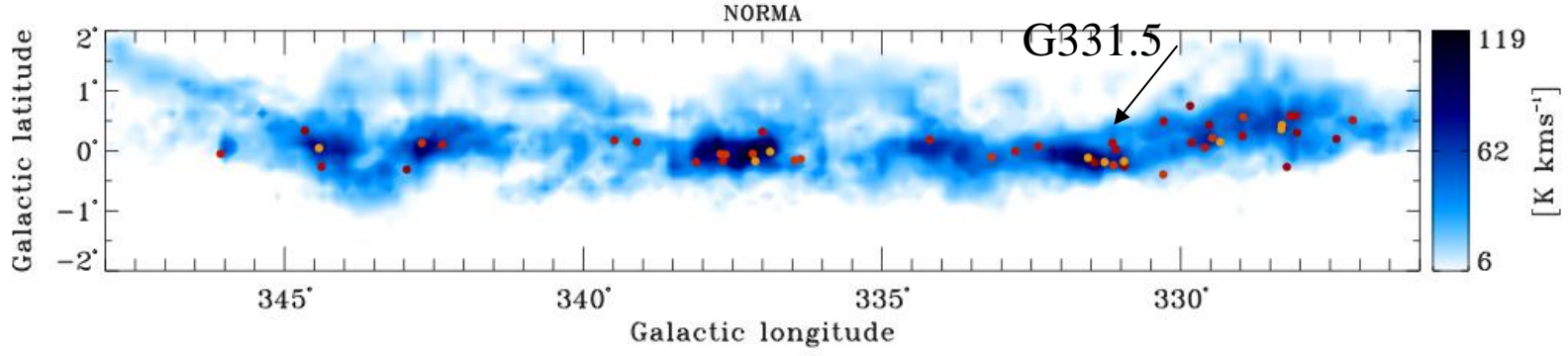
*Central map: disk or
projected shell

*Gray/white crosses:
Blue/red outflow lobes.

- Outflow inclination = 10°
- Resolution: 1 arcsec

M. Merello Thesis

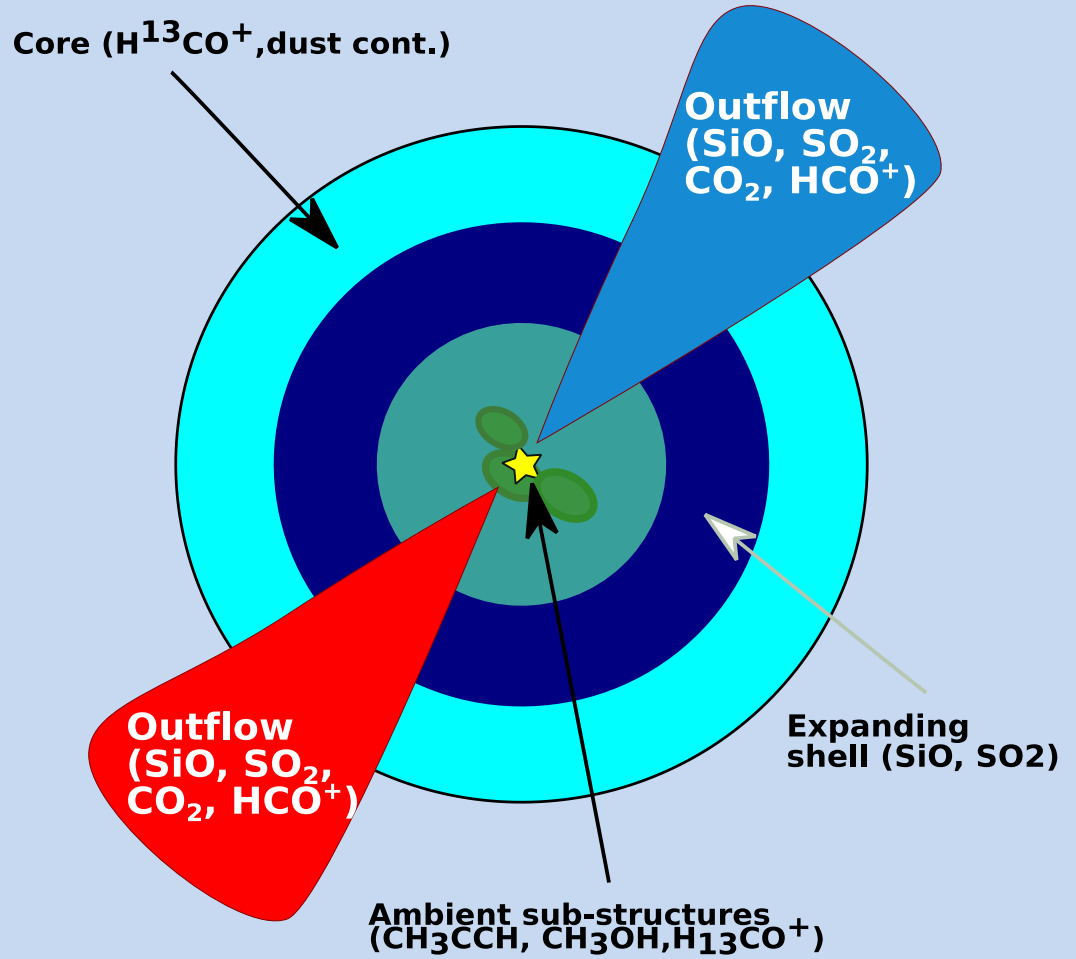




MINI:
Resolution
480''
(1985)

Sketch model of G331.5
Molecular Outflow

ALMA Resolution: 1''
(2012)



C. Hervías Thesis

Nicolas Duronea (IAR)

- In the meantime: relocation of the Southern MINI to Cerro Calán, (OAN, Universidad de Chile, 2005-2009)

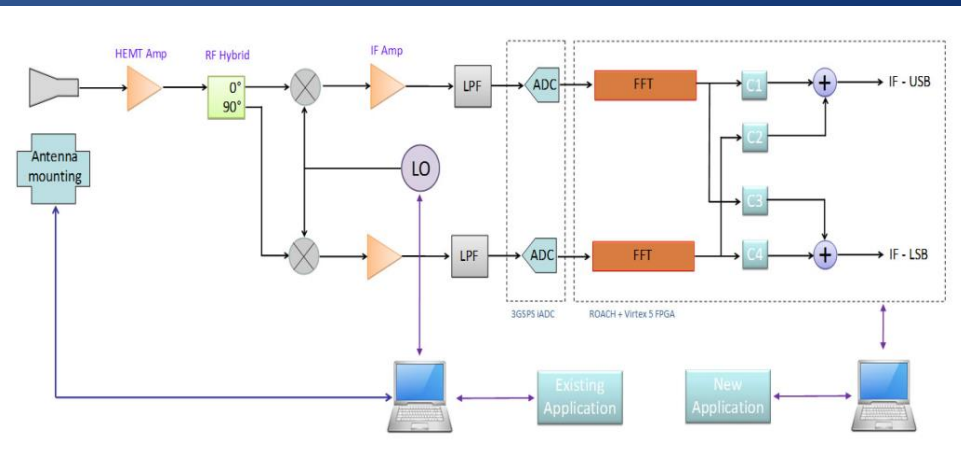


■ The 1.2 m telescope at U. Chile OAN, Cerro Calán

- Hands-on training for Astronomy students
- Engineering graduate and undergraduate theses.
- Receiver upgrade with hybrid mixer and FPGA digital SB separation spectrometer
- SCIENCE: Finish up all sky survey for gamma ray foreground ID



Southern Mini at Cerro Calán, July 2013



Digital sideband separating mixer using FPGA technology (ROACH; R. Finger, R. Rodriguez).

The U. Chile Millimetre Wave Laboratory (2005) Centre for Astrophysics and Associated Technologies (2008-)



- Joint effort of Astronomy and Electrical Engineering.
- Development of front-end and digital back-end technology
- Training of undergrad and grad students (joint PhD program)
- International collaboration in state-of-the-art projects:
- **ALMA Band 1 Receiver Prototype (2008-2012)**

Main Current Projects

- 1. ALMA Band 1 Optics full design and fabrication**
- 2. ALMA Band 2+3 Optics design and prototype**
- 3. LLAMA Bands 1 and 3 Heterodyne Receivers**
- 4. FPGA-based Digital Spectrometers**
- 5. 1.2 m Mm-wave Telescope upgrading**
- 6. Technology transfer**



MM-WAVE LAB MACHINE SHOP:
KERN CNC MILL (CATA, 2008)
SCHAUBLIN CNC LATHE (QUIMAL, 2014)

ALSO: PHOTONICS LAB AT FCFM
(QUIMAL 2015)



BAND 1 HORNS MACHINED WITH NEW LATHE (2015)
Formerly 1 week; now one hour

International Collaborations



North America
NRC-HIA, Canada;
NRAO, USA (Band 1)

Europe
ESO and others
(Band 2+3); SRON,
Netherlands (Band 9),..

East Asia
ASIAA, Taiwan);
NAOJ (Japan)) (Band 1)

South America
ALMA
Argentina-Brazil: Large
Latin American Millimeter
Array (LLAMA)

China
National Astronomical
Observatory (NAO/CAS)
FPGA spectrometers

Muchas Gracias y Feliz Aniversario 50 IAR !



2009 September