COSMIC DAWN

The first 5 Years of ALMA!

Anneila Sargent
Caltech
ALMA Solar System Program

PLUTO & CHARON

- Decreased Pluto positional uncertainty
- Astrometric accuracy 4 mas (100 km)
“Standard” picture of star formation (Shu+’87)
DETECTION OF INFALL IN THE PROTOSTAR B335 WITH ALMA

Neal J. Evans II, James Di Francesco, Jeong-Eun Lee, Jes K. Jørgensen, Minho Choi, Philip C. Myers, and Diego Mardones

Evans et al. (2015)

Central velocity: Static outer envelope

Low velocities: Infall in outer shells

Line wings: Infall in Inner region
Hull, Mocz, Burkhart+2016, submitted
A protostellar system revealed by ALMA

L1527 IRS

Rotating infalling envelope: CCH, c-C$_3$H$_2$, CS, and H$_2$CO
Centrifugal barrier: SO
Disk: CH$_3$OH

Sakai et al. 2014
Chemical characteristics

Protoplanetary disk stage:
  Three layers of chemistry
    Hot atomic layer (PDR)
    Warm molecular layer (Hot Core chemistry)
    Cold icy layer (cold prestellar core chemistry)

A major question: Does disk material remain as inherited from the ISM, or is it significantly altered within the disk?

→ systematic ALMA observations of disks of embedded protostars.
Proto-planetary Disks from ALMA

HL Tau
ALMA Partnership et al. +LP 2016

V883 Ori
Cieza et al. 2016, Nature

TW Hya
Andrews et al. +LP 2016

L1448 IRS3B
Tobin et al. +LP 2016
Nature, in press

Elias 2-27
Pérez et al. 2016
Science, in press

Elias 24
Di Pierro et al. +LP in press

Laura Pérez - ALMA 5 years - September 22, 2016
First direct evidence of instability in a young disk

Elias 2-27 – 0.5 $M_{\text{sun}}$
Class II ~1-3Myr old

Other interesting disk studies:

- HD 163296 – planets? (Isella)
- TW HYA – pebbles? (Schwarz)
Millimeter-wave Polarization in a Transition Disk

Peak polarization = 3.28 +/- 0.03 %

If B-field: toroidal on the main ring, poloidal outside.

Self-scattering naturally explains P-vectors flip.

Kataoka et al. (submitted)
ALMA’s Transition Disks

Brenda Matthews Review

AA Tau – a ring system in a transition disk? (Loomis)
β Pictoris exocomets from resolved CO

Dent+ 2014, Matrà+ 2016 on arXiv today and in prep

2 CO clumps from collisions of exocomets in resonance with unseen b Pic c planet

Tails from CO photodissociation after ~300 yrs
Stars & Stellar Evolution

H-R Diagram

- **Red Super Giants**
  - $M_{\text{initial}}$: 8 - 35 $M_\odot$
  - e.g. Betelgeuse, Antares

- **Asymptotic Giant Branch**
  - $M_{\text{initial}}$: 1 - 8 $M_\odot$
  - e.g. Mira

Planetary Nebula
- (10,000 years)

LIZ HUMPHREYS: ALMA Conference 2016
AGB STars

Detached Shells

TT Cyg
IRAM PdB
CO (1-0)

Olofsson et al.
2000

60 arcsec

ALMA Conference 2016
Detached Shells – the ALMA View

R Sculptoris

Maercker et al. (2012)
Mira: Resolving the Binary

Vlemmings et al. 2015, Matthews et al. 2015, Wong et al. 2016

ALMA Band 3: 90 GHz

ALMA Band 6: 230 GHz

Size of Mira A is ~4.0 x 3.6 AU at ALMA Band 6
25 mas resolution at Band 6 (2.3 AU); ALMA 15 km
Hotspot on Mira A?

ALMA Long Baselines

Stellar disk model subtracted
Stellar disk plus hotspot subtracted

Hotspot $T_b=10000$ K $\sim 0.4$ AU, likely due to magnetic activity

Vlemmings et al. (2015)
Mira: Extended SiO Plume

ALMA Long Baselines

Giant tail of SiO $v=0$ emission

Band 6

Wong et al. 2016
Mira: Interacting Winds

Ramstedt et al. 2014, ALMA CO (3-2)

Spiral structure and bubble from binary interaction
Massive Star Formation

• ALMA beginning to address:
  – gas flows in filaments, protocluster forming clumps, fragmentation, origin of IMF
  – collapse/infall and accretion disks (kinematics difficult to extract due to high optical depth of dust continuum emission)

BUT

• Most published ALMA results are case studies – many posters
• **Surveys of carefully selected samples needed.**

• ALMA Polarization and Zeeman observations
  – role of magnetic fields in star formation
OMC 2/3 Filament

Lis et al 1998

3mm

N$_2$H$^+$ 1-0/8μm

Yue and Zhu, see also Kainulainen+ 2016
Global Collapse in SDC335

Peretto+ 2013
See poster Hasegawa
Global collapse and spiral structures

Massive protocluster G33.93+0.11
L~ 2.5x10^5 Lsun, M=3000Msun <1pc
Liu et al. 2015

Massive protocluster W33A
L~ 2.5x10^4 Lsun, M=1000Msun <1pc
Poster by Maud
Also Galvan-Madrid 2010
Explosive outflows in OMC1 → Dynamical interaction

SMA, CO 2-1
Zapata et al 2009

H$_2$ Bullets: Grey scale
Explosive outflow in CO 2-1

Proper motion of three massive stars at center of outflow suggest common spatial location ~500 years ago

L$_{bol}$ ~10$^5$ L$_{sun}$ (Orion BN/KL)
M ~ 10 M$_{sun}$
E ~ 10$^{47}$ Erg
High vel. >100 km s$^{-1}$
Very poor collimated (degree of collimation 200° – 300°)
Bright in optical and infrared bands

(Disclosed by Allen & Burton in 1993)
ALMA View

Explosive outflows in CO 2-1 caused by Src I/n/BN interaction 500yrs ago
Bally+ in prep

See Plambeck+Wright 2016 on disk in Src I
Posters by Plambeck, Hirota, Marcelino
An ALMA view of the W43-MM1 mini-starburst protocluster

Louvet et al. (2014)

Extraction of ~500 sources with the Getsources extraction tool (Men’shchikov+2012)

Reduced to ~280 sources after physical analysis (Nony et al. in prep)

1.3 mm
Scales 0.5”-7” (with ACA & TP)
Mass completeness: ~ 0.6–3\(M_\odot\)

F. Louvet, Half a decade of ALMA
An ALMA view of the IMF origin in the mini-starburst protocluster of the W43-MM1 ridge

~300 pre- and proto-stellar cores of 2500 AU size. The 3-100 $M_\odot$ part of the CMF is much flatter than the IMF.

Possible evolutions:

- OB star feedback will steepen the final IMF
- The high-mass cores will fragment (below 2500 AU)
- Core mass = available mass for accretion?
- SFE increases with $<n>$

The IMF will be atypical?

(Motte, Nony, Louvet et al. in prep.)

See also Hatchell & Fuller+2008, Myers+2009b

F. Louvet, Half a decade of ALMA 9/11
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CMF in W43-MM1

$N_{core} \propto M^{-1.1}$

IMF (Kroupa)

$N_{star} \propto M^{-2.3}$

Completeness limit

F. Louvet, Half a decade of ALMA
Star Formation over Cosmic Time (Tacconi Review)

~ 90% of the cosmic SFR occurs on the MS
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Continuous Accretion from Halo and Disk Instabilities

Hopkins+12

(Major) Mergers and Starbursts

Dekel+09

Continuous Accretion from Halo and Disk Instabilities
The Equilibrium Physics of Galaxy Evolution

- Mass Accretion
- Star Formation
- Structural transformations
- Outflows

Star Formation at R ~ 1 kpc

Quenching & build-up of "Red Sequence"

Mass accretion rate at R ~ 1 kpc...
ALMA Contributions

• ALMA dust pointed and blank continuum surveys statistical global dust (and gas) properties
  *talks: N. Scoville, F. Walter*

• Added to wealth of data from CO surveys at other facilities and Herschel surveys; beginnings of self-consistent picture of gas scalings,

• Dusty submm population very well studied and characterized (SMGs, etc)
  *talks: Casey; Hodge; posters: Gullberg, Iono, Riechers talk:*

• Spectacular results from high resolution observations of highly magnified gravitational lenses
  *talks: J. Spilker, C. Sharon; posters: M. Rybak, G. Walth*

• CII and other fine structure tracing the ISM tracer out to highest redshifts - quantitative interpretations still uncertain. Need careful calibrations
  *talks: Aravena, Inoue, Pavesi, Lu, Neeleman; posters: Diaz-Santos, Fujimoto*
ALMA Detects Molecular Outflow in a Massive, Compact z=2 SFG

$M_{\text{gas}} = 3.5 \times 10^{11} \, M_\odot$

$\Sigma_{\text{gas}} > 10^{10} \, M_\odot / kpc^2 \, \text{ (within } R_e \text{) (several } 10^2 \text{ mag)}$

Powerful nuclear outflow

$V_{\text{rot}} = 370 \, \text{km/s} \quad R_e = 2.4 \, \text{kpc}$

Talks by J. Spilker & H. Russell
SDP.81 – A Gravitationally Lensed z=3.042 Galaxy Case Study in Dynamics and Clump Properties

- Clumpy, rotating disk
- Clump/cloud properties on ~100-200 pc scales
- $V_{rot} = 320$ km/s; $\sigma \sim 30$ km/s
- Toomre unstable gas disk
- Clouds/clump pressures $10^4$x typical MW GMC – more like GC clouds
- 1.5 kpc molecular disk embedded in but offset from 6 kpc stellar disk

The ALMA Partnership+14, Dye+15, Hatsukade+15, Rybak+15a,b, Swinbank+15, Tamura+15, Wong+15, Hezaveh+16, Inoue+16

Talks: J. Spilker, C. Sharon & Y. Hezaveh
Posters: M. Rybak & G. Walth
[CII] as an ISM Tracer at $z>4$

- Large observational uncertainties on SFRs, $z$, UV slope, etc
- Detections @ $z\sim5-6$ obey local CII-SFR relation for low metallicity dwarfs
- $z\sim7$ detections fall below the local relations and below $z\sim5$ LBGs with similar SFRs: evolution and metallicity effects?

Talks by A. Inoue, R. Pavesi N. Lu, M. Aravena; posters by Diaz-Santos, Fujimoto

The CII/FIR ratio correlates well with $\Sigma_{\text{FIR}}$, down to at least 300pc scales. Applies for AGN and star-forming objects equally.

The OH 119um doublet is good for determining mass outflow rates and wind structure (Cycle 4 A priority, PI Spilker)
What determines distribution of gas across galaxies?

The Gas Supply

ALMA’s resolution can map gas in the close vicinity of central SMBH (also handy for BH mass measurement - see talk by Barth)

In NGC 1097, HCN kinematics track gas flows to within 40 pc of the AGN.

KARIN SANDSTROM: ALMA Conference 2016
Kepley et al. (2016) finds molecular clouds in very low metallicity starburst galaxy II Zw 40 (1/5 Z_⊙) shows X_{CO} \sim 18 X_{CO,MW}
The Star-Forming Gas Supply

For low metallicity regions, ALMA’s high sensitivity lets CO be mapped even if there is very little of it.

Rubio et al. 2016 - CO in WLM dwarf confined to small central region of clouds

see Monica Rubio’s talk next
ALMA has shown us so far:

- **Transport of molecular gas** to inner parts of galaxies, potentially feeding SMBHs and driving starbursts
- A **variety of outflows** driven by SF or AGN, carrying away substantial fractions of central $H_2$
- The **drivers of $X_{CO}$ variations**, the transition from CO-dark to CO-bright gas in low $Z$ clouds, cloud characteristics of “starburst” like $X_{CO}$
- **Environmental dependence of cloud populations**
- **Connection between cloud properties and SFE**
- **Evolution of clouds** as they form, form stars and dissipate
- **Next: systematic, statistical studies of the full galaxy population**
ALMA’s View of the Obscured Universe at High Redshift

Caitlin Casey: ALMA Conference 2016
A Blank Field 2mm Deep Survey in COSMOS
63 hour large program, 230 arcmin² to 80μJy RMS at 2mm (band 2)

Goal: Constrain $40 < \text{SFR} < 1000 \text{ M}_\odot/\text{yr}$ galaxies beyond $z \sim 5$
Obscuration to Reionization:
A Blank-Field 2mm Deep Survey in COSMOS

63 hour large program, 230 arcmin$^2$ to 80uJy RMS at 2mm (band 4)

Goal: Constrain 40 < SFR < 1000 $M_{sun}$/yr galaxies beyond z~5

ALMA Conference 2016
Obscuration to Reionization:
Blank-Field 2mm Deep Survey in COSMOS

Our large program, 230 arcmin² to 80uJy RMS at 2mm (band 4)

Goal: Constrain 40 < SFR < 1000 M_{sun}/yr galaxies beyond z~5

These galaxies become the earliest massive galaxies.
Yet they are unconstrained!
Evolution of ISM, SF, & Accretion in Universe

major questions:

• how does ISM content vary w/ z – like SF ?

• SB vs MS – is higher SFR due to more ISM or higher SF efficiency

• ISM content vs $M_{stellar}$

• gas depletion time variation w/ $z, M_{stellar}, SFR$ rel. to MS

• depletion timescale short $\Rightarrow$ IGM accretion $\Rightarrow$ rate of accretion?

RJ continuum optically thin, $S_{\nu} \propto T_{\nu} \frac{\kappa \nu}{\text{gas}} M_{\text{gas}}$
Summary

summary:

1. RJ dust continuum is fast (2min) and reliable
2. ISM content and SFE evolve each less rapidly w/ z than SFR
3. ISM mass varies as $M_{\text{stellar}}^{1/2}$
4. above MS, SB due to both increased ISM and higher eff.
5. accretion is huge (100 $M_{\odot}$ yr$^{-1}$)
   
   accretion rate / $M_{\text{stellar}}$ lower for higher stellar mass
Different (complementary!) approaches

Single dish bolometer (sub)millimeter maps:
locate DSFGs, number counts, clustering, etc.

Ever increasing covered areas:
From <1 deg$^2$ with SCUBA/MAMBO/LABOCA
To >100-1000s deg$^2$ with Herschel/SPT and SCUBA-2

follow-up of optically-selected sources [presentation by Linda Tacconi, Nick Scoville, Jackie Hodge, Yiping Ao, Wang]

ALMA continuum deep fields [e.g. Dunlop et al. 2016, presentation by Umehata, posters by Zwaan/Otea, Hatsukade, Arancibia]

Walter et al approach  Molecular Deep Field through Spectral Scans

Field of choice: Hubble Ultra Deep Field
ALMA UDF: ASPECS pilot program

40h ALMA spectral scans in the UDF (Aravena & Walter): complete CO coverage @ z>0, [CII] @ z=6-8

Walter et al. 2016
ASPECS ALMA Large Program

Pls: Aravena, Carilli, Walter

Very significant increase in area (and depth) over the pilot program.

Approved 150h ALMA Large Program in cycle 4