MOLECULAR CLOUD AND STAR FORMATION IN THE EXTREME OUTER GALAXY

Natsuko Izumi[1], Naoto Kobayashi[1], Chikako Yasui[1], Alan T. Tokunaga[2], Masao Saito[3,4], Satoshi Hamano[1]
1 University of Tokyo, 2 University of Hawaii, 3 National Astronomical Observatory of Japan, 4 Graduate University for Advanced Studies

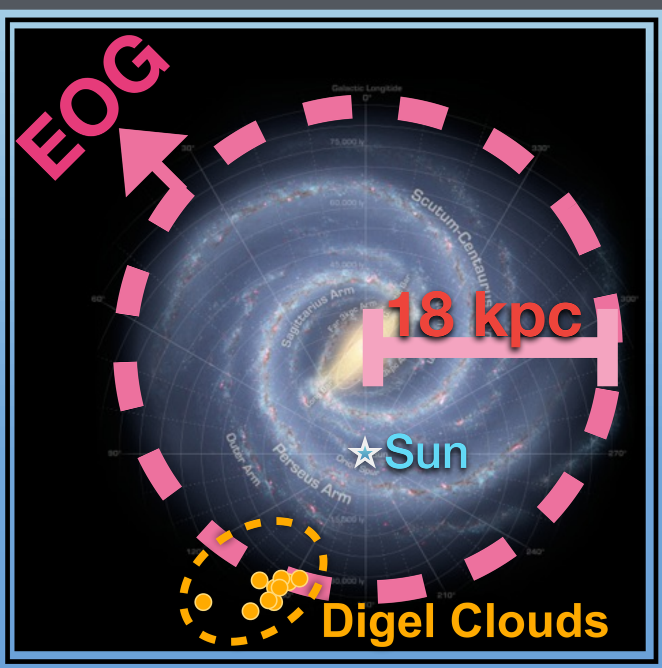


Figure 1 : Image of the our Galaxy (NASA/JPL-Caltech)

Abstract

We report the physical quantities of molecular clouds in the extreme outer Galaxy (EOG) at Galactocentric radii greater than 18 kpc. The EOG is the valuable place where it is possible to observe the "galaxy formation processes" in the scale of a molecular clouds (pc-scale). We performed high-resolution ^{12}CO(1-0) observation of 8 molecular clouds in the EOG with the Nobeyama radio observatory (NRO) 45 m telescope to detect 352 clumps and identified 23 new candidates of star-forming region. Some properties of these clumps (Mass spectrum, Virial mass - CO luminosity relation, Size - velocity width relation)are apparently different from those in the other part of the Galaxy, which could indicate that the environment has an impact on molecular cloud/star formation activity.

1.Introduction

■ Extreme outer galaxy (EOG)

- **Galactocentric radius (R_G) ≧ 18 kpc**
- **Environment**
  1) Little or no perturbation from the spiral arm
  2) Low gas density (e.g. Wolfire et al. 2003)
  3) Low metallicity (e.g. Smartt & Rollenston 1997)

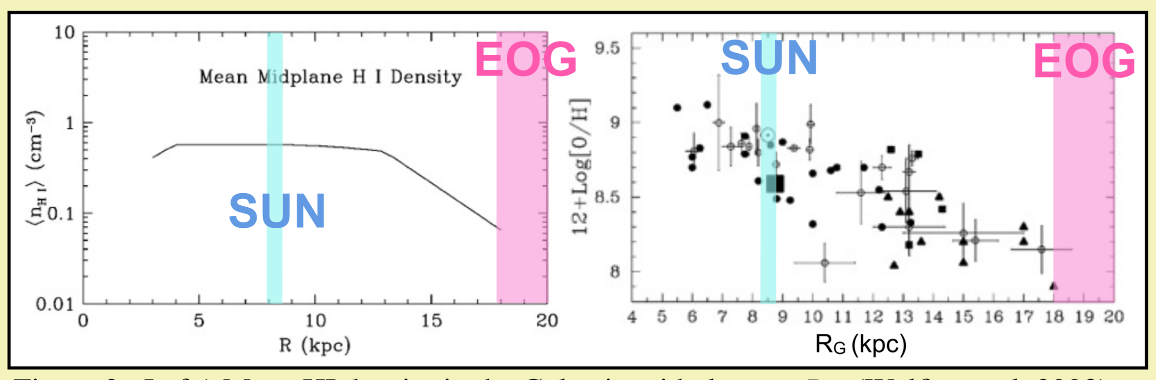


Figure 2 : Left) Mean HI density in the Galactic mid plane vs R_G (Wolfire et al. 2003)
Right) Oxygen abundance as a function of R_G for B-type stars (*open circles*) and HII regions (*filled symbols*) (Smart+Rolleston 1997)

Such environments may have similar characteristics that existed **in the early phase of the formation of the Galaxy** (Kobayashi et al. 2008)

The EOG is the valuable place where it is possible to investigate molecular cloud/star formation activity under such an interesting environments in the scale of a molecular cloud (pc-scale) !!

■ Our objective

- **Derive physical quantities of molecular clouds and fundamental parameters of star formation**
  1) Molecular cloud mass, size, velocity width …
  2) Star formation efficiency (SFE), rate (SFR) …

Are there any difference between the EOG and the other part of the Galaxy??

2.Observation

■ Target : Digel Clouds

- **Discovered by the very first survey of molecular clouds in the EOG (Digel et al. 1994)**
- **Composed of eight molecular clouds (Cloud 1-8)**
  - Star forming regions are clearly detected in **Cloud 1** and **Cloud 2**

Star formation activity in perhaps the most distant molecular cloud (R_G ~ 22 kpc : kinematic distance)

(Yasui et al. 2006,2008 ; Izumi et al. ApJ accepted)

■ CO mapping

Obs. date	2006/3, 2007/12	2014/2, 5
Target	Digel Cloud 1-2	Digel Cloud 3-8
Telescope	Nobeyama (NRO) 45m telescope	
Line	12CO (J=1- 0)/115 GHz	
Velocity resolution	0.25 km s	
Effective HPBW	~ 17″	~ 17″


Figure 3 : NRO 45 m telescope (NAOJ)

3.Results

■ Molecular cloud distribution

- **High-resolution observation enabled us to map overall structure of the clouds in about 1 pc-scale**
  1) Detection of **352 clumps** (using CLUMPFIND by Williams et al. 1994)
     - Detection limit : **L_{CO} = 2.2 K km s^{-1} pc^2 ; M_{CO} = 7 $M_\odot$** (← Assuming X_{CO}= 2.0×10^{20} cm^{-2} (K km s^{-1})$^{-1}$)
     - Typical size : **r = 1 ~ 3 pc ; dv = 0.7 ~ 1.5 km s^{-1}**
  2) Identification of **23 new candidates for star forming region**

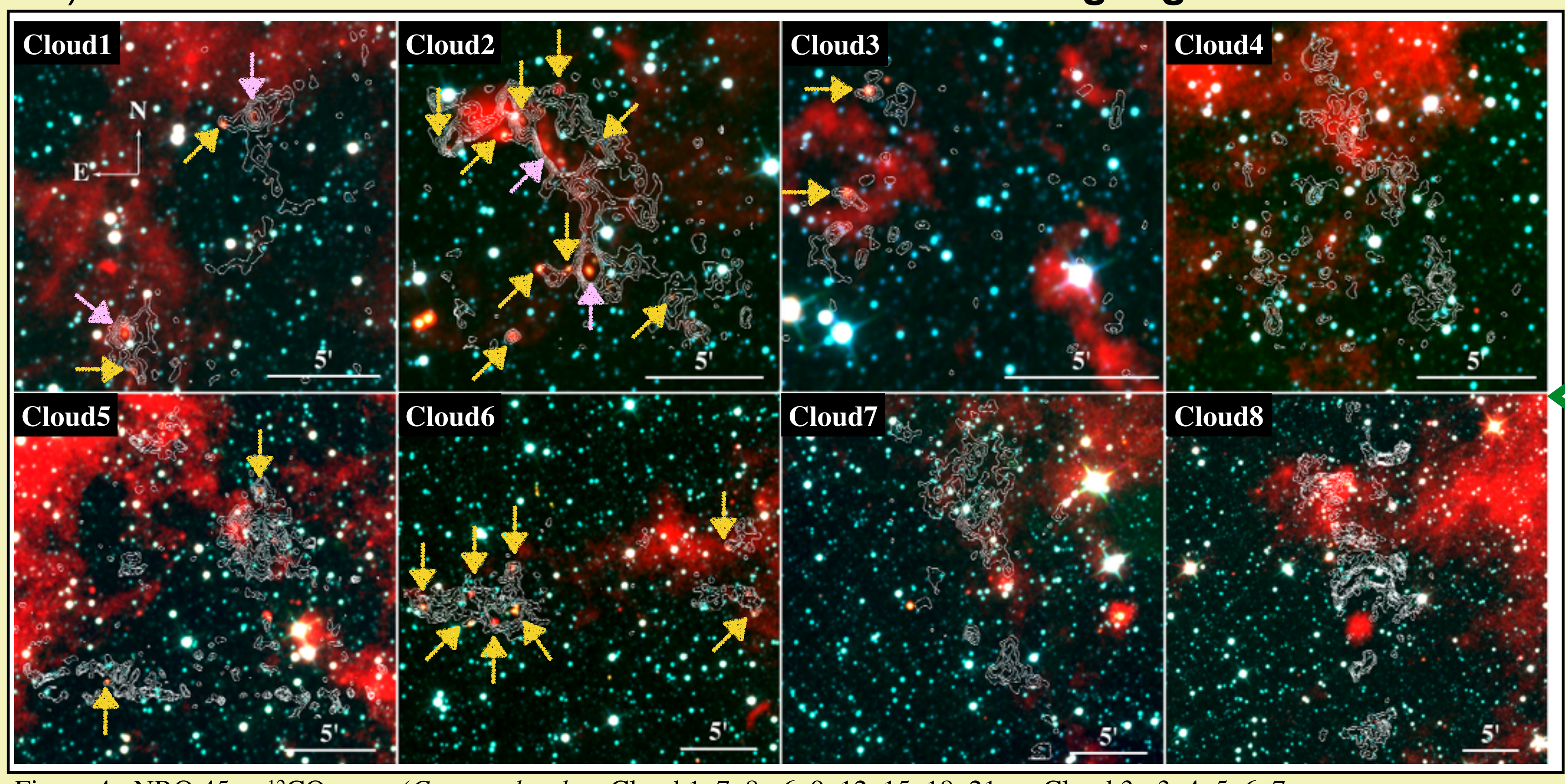


Figure 4 : NRO 45 m ^{12}CO maps (*Contour levels* - Cloud 1, 7, 8 : 6, 9, 12, 15, 18, 21 σ ; Cloud 3 : 3, 4, 5, 6, 7 σ ; Cloud 4,5 : 4, 5, 6, 7, 8 σ ; Cloud 6 : 5, 7, 9, 11, 13 σ) and mid infrared pseudo color images around these Clouds. The color images are produced by combining the 3.4, 4.6, 12 μm images from the WISE data (NASA/IPAC).

Star forming region
← : Already-known
← : New candidate
Star forming regions are detected in the MIR images as compact reddened stellar object

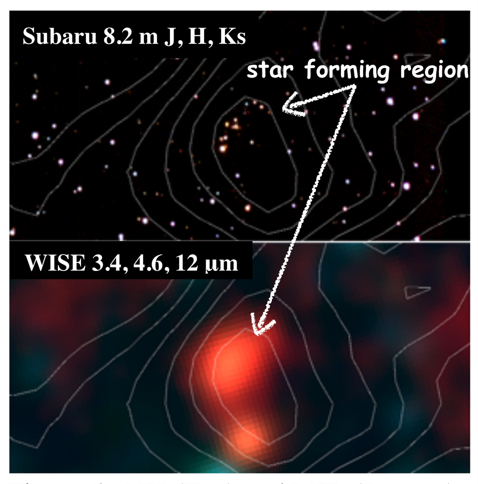


Figure 5 : NIR(Top) and MIR (Bottom) pseudo color image of the star forming region in Cloud 1

4.Discussion

■ Properties of clumps in Digel Clouds (Cloud 1-8)

- **Mass**

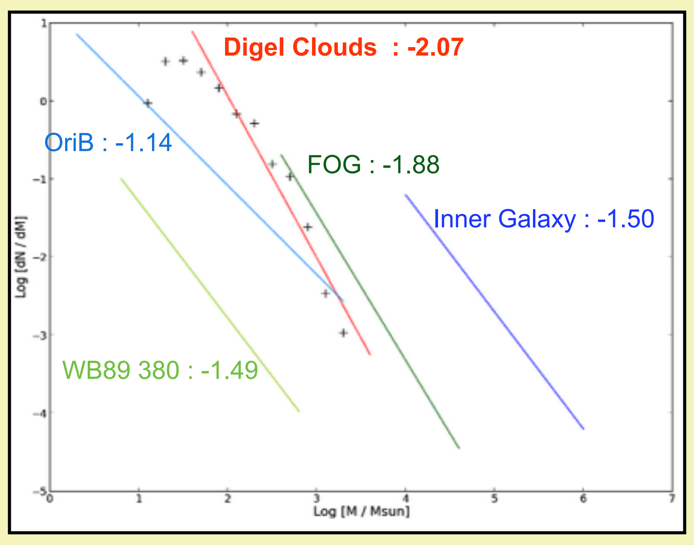


Figure 6 : Clump mass distribution of Digel Clouds. Color lines show the fitting slope of the mass spectrum (*Red* : Digel Clouds ; *Green* : Far outer Galaxy at R_G = 13.5 ~ 20.3 kpc by Snell et al. 2002 ; *Blue* : Inner Galaxy at R_G = 1.5 ~ 12 kpc by Solomon et al. 1987 ; *Light blue* : Orion B South ; *Light Green* : WB89 380 at R_G = 16.6 kpc by Brand et al. 2001).

- Assuming : CO-to-H$_2$ conversion factor **X_{CO}= 2.0 × 10^{20} cm^{-2} (K km s^{-1})$^{-1}$** (Bolatto et al. 2013)
- Almost all clumps are **smaller than 10^3 $M_\odot$**
- Power-law slope of mass spectrum : **-2.07 ± 0.19** (Range : > 40 $M_\odot$)

+ **GMC is virtually absent in EOG ??**
+ Power-law slope of mass spectrum in the EOG is **steeper** than that of in the other part of the Galaxy??
  (Same result : Snell et al. 2002 ; Opposite result : Brand et al. 2001)

➡ It has an impact on Initial mass function (IMF) ??
Germany et al. (1982) and Wouterloot et al.(1995) found that at R_G > $R_\odot$ (= 8.5 kpc) the slope of the IMF becomes steeper.

- **Virial mass and CO luminosity**

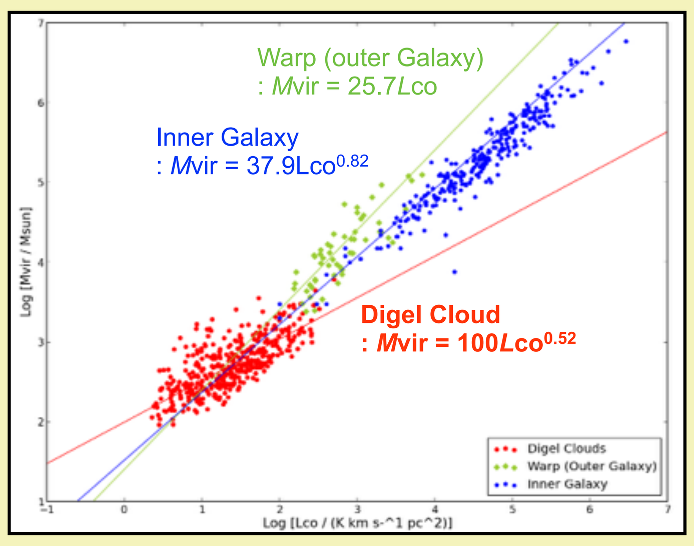


Figure 7 :Virial mass as a function of the CO luminosity (*Red* : Digel Clouds ; *Blue* : Inner Galaxy at R_G = 1.5 ~ 12 kpc by Solomon et al. 1987 ; Light *green* : Southern Galactic Warp at R_G = 14.5 ~ 19 kpc by Nakagawa et al. 2005).

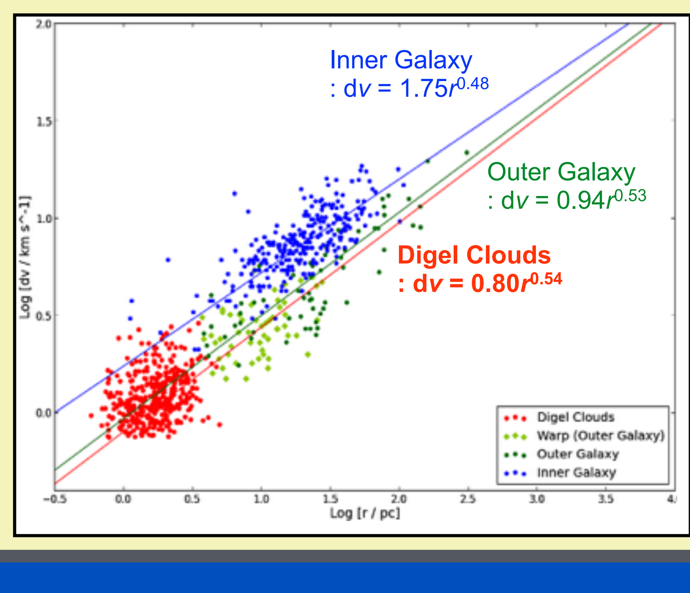
- Mco of almost all clumps are **smaller than virial mass**
- Virial mass - CO luminosity relation in Digel Clouds : **M_{vir} = 100 $L_{CO}^{0.52}$**

+ The slope is **less steep** than the other part of the Galaxy

➡ Almost all clumps in the Digel Clouds **are not virialized** ??
or
CO-to-H$_2$ conversion factor X_{CO} in the EOG is **different** from that in the other part of the Galaxy??
(Same interpretation : Nakagawa et al. 2005 ; Opposite interpretation : Brand & Wouterloot 1995, Snell et al. 2002)

↑ **Dark mass (Dark molecular cloud mass) fraction** in the EOG is **large**?? (Wolfire et al. 2010; Bolatto et al. 2013)

- **Size and velocity width**



- Size - velocity width relation in Digel Clouds : **dv = 0.80 $r^{0.54}$**

+ The slope is **steeper** than that of the inner Galaxy (R_G = 1.5 ~ 12 kpc) **similar** with that of the outer Galaxy (R_G = 8.5 ~ 19 kpc)

➡ The relation of r-dv in the outer Galaxy holds in the range of **r = 1 to 100 pc**

Figure 8 : Size-linewidth relation of the clumps in Digel Clouds (*Red* : Digel Clouds ; *Blue* : Inner Galaxy at R_G = 1.5 ~ 12 kpc by Solomon et al. 1987 ; Light *green* : Southern Galactic Warp at R_G = 14.5 ~ 19 kpc by Nakagawa et al. 2005 ; *Green* : Outer Galaxy at R_G = 8.5 ~ 19 kpc by Sodroski et al. 1991 ; Brand & Wouterloot. 1994). *Blue* and *Green* line show least-squares fits through the inner (*Blue*) and outer (*Green*) Galaxy (Brand & Wouterloot, 1995)

5.Future Work

■ Conduct other clump detection methods (e.g. CPROPS)

■ ^{13}CO (& C^{18}O) observations of Digel Clouds

■ Increase the number of samples in the EOG