Identification and Characterization of Massive Dark Clouds in the Outer Galaxy

Show-case: G111.80+0.58

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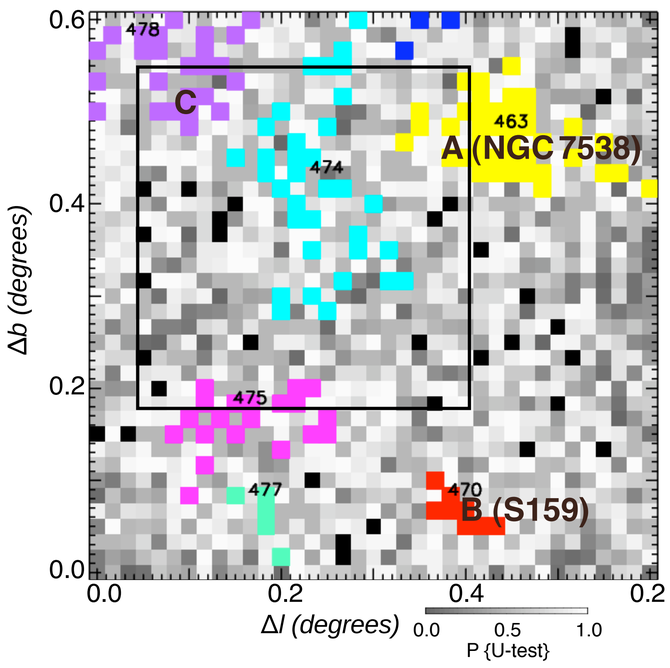
Abstract

We present the outline of a possible method to identify massive dark clouds in the Outer Galaxy, exemplified by G111.80+0.58. The procedure employs a statistical measure of near-IR stellar color distributions and a comparison with existing surveys. The goal is to find objects similar to Inner Galaxy Infrared Dark Clouds (IRDCs), i.e., the very early, cold stages of clustered star formation. Conventional identification of IRDCs (through mid-IR extinction) is not possible in the Outer Galaxy due to a lack of bright background emission. So far, star formation studies in the Outer Galaxy focus mainly on the more advanced stages of evolution. Follow-up molecular line observations enable us to characterize G111.80+0.58 and show that this approach can indeed be successful.

Identification method

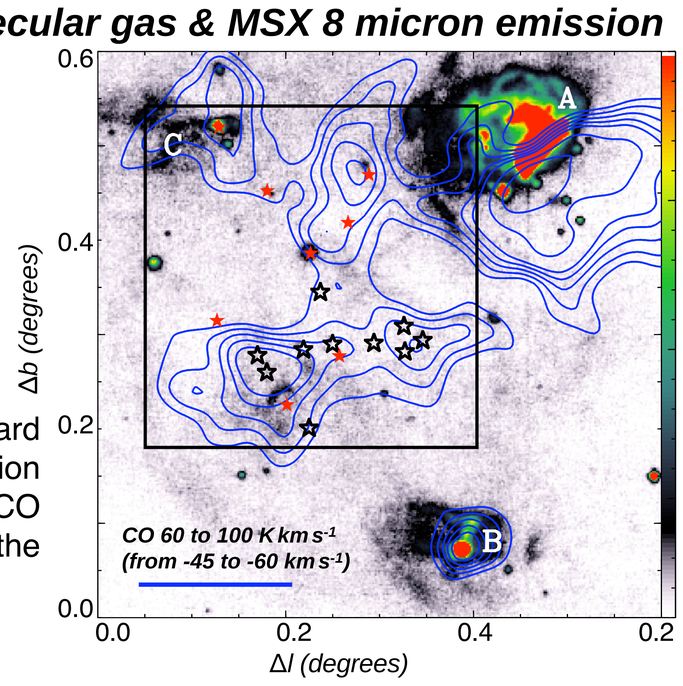
1: Structures of red sources in 2MASS



On a predefined grid, the Mann-Whitney U-test is used to calculate the probability, P(U), that the near-IR (*H-K*) color distribution of stars toward each line of sight is different compared to the local distribution. Cells with P(U) ≥ 99% are selected as initial targets.

A Friends-of-Friends technique identifies clusters of 4 or more cells in projection on the sky (colored regions). Remaining, isolated cells are marked black. G111.80+0.58 has ID tag 474. Note the clear identification of well-known regions as well.

2: Molecular gas & MSX 8 micron emission



MSX 8 micron emission (image) traces warm dust, e.g., toward the star forming complex NGC 7538. The lack of bright emission toward G111.8+0.58 suggests a relatively quiescent stage. CO observations from the FCRAO survey (contours) show the presence of molecular gas at a velocity around -55 km s^{-1}.

- Black box: outline of the region observed in $C^{18}O$ (bottom Figure)
- A & B: NGC 7538 and S159, respectively -- C: maser/radio emission
- Color scale in 2,3 & 5: MSX 8 micron emission ranging from 1–20 × 10^{-6} W m^{-2} sr^{-1}

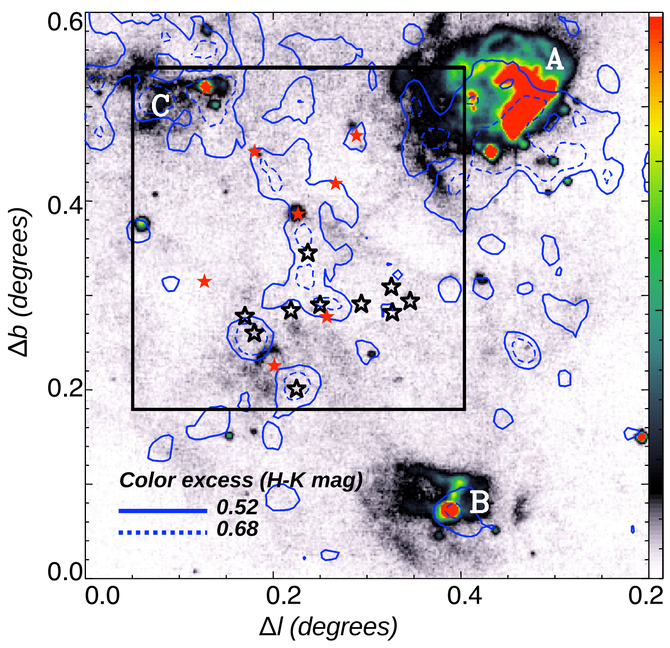
474 - ID number of 2MASS structure

★ - Target positions for line observations (cores)

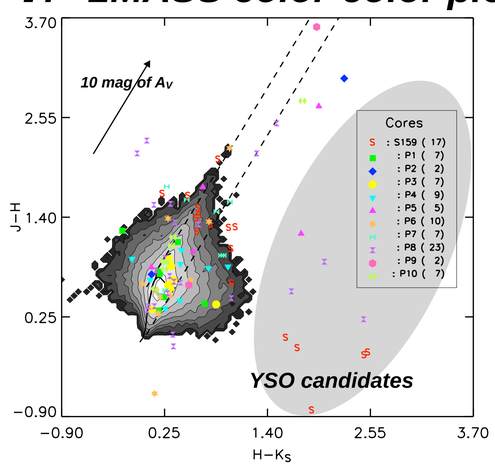
★ - IRAS point sources

Legend for Figures

3: 2MASS color excess

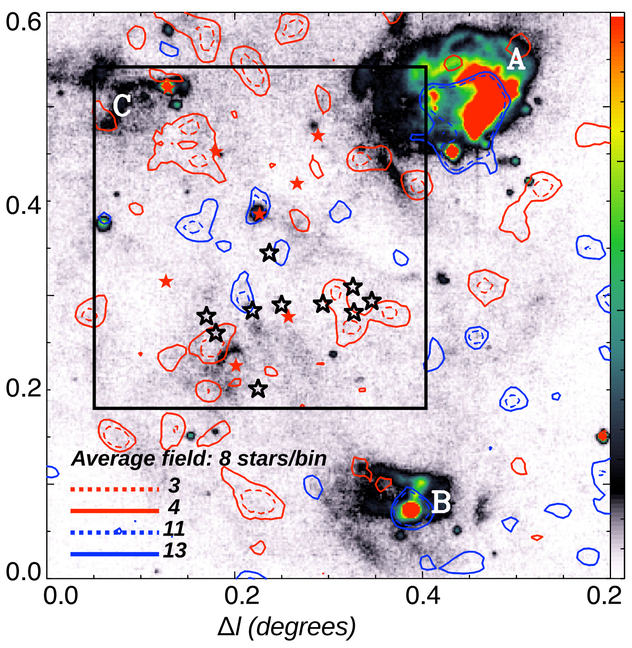


4: 2MASS color-color plot



Average *H-K* colors (left) show a significant near-IR color excess. The contours correspond to 6 and 8.5 mag of A_V (peak >15 mag). A number of 2MASS sources resemble colors of YSO candidates (above). Star counts (right) show that some areas have a deficit, others a surplus in stars.

5: 2MASS stellar distribution



Characterizing dense cores in G111.81+0.58

Molecular lines observed

toward P1 to P10 (right)

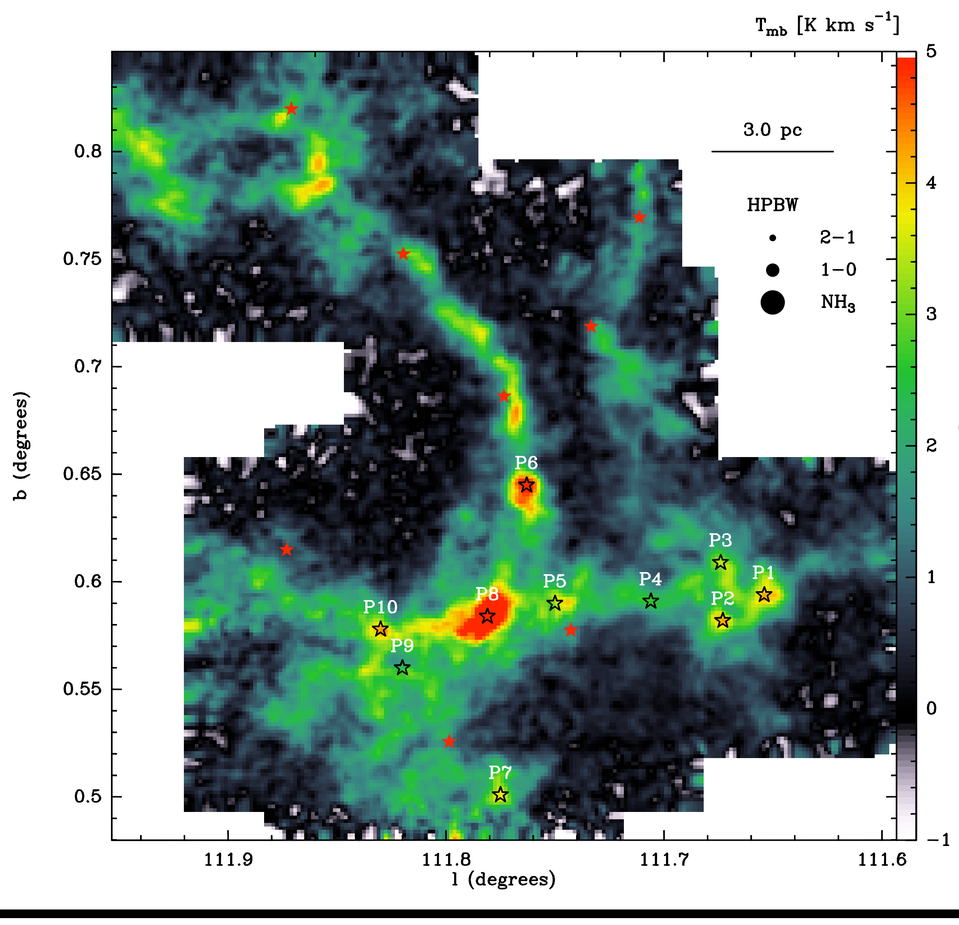
$C^{18}O$ (1-0) map using HERA (IRAM 30m)

Single pointings of $C^{18}O$ (1-0) & (2-1), ^{13}CO(1-0) & (2-1), $C^{34}S$(2-1) using IRAM 30m

NH_3 (1,1), (2,2) & (3,3) using Effelsberg 100m

Derived core properties

Size: (50% of $C^{18}O$ peak @ distance of 3.1 kpc)	**0.6–1.2 pc**
Temperature:	**7–20 K**
FWHM:	**1–2.5 km s^{-1}**
Column (H_2):	**5–75 ×10^{21} cm^{-2}**
Mass$_{LTE}$:	**20–1000 M$_\odot$**



Conclusions

Over 1300 clustered red regions are identified using 2MASS. Many coincide with well-known objects, but some, like G111.80+0.58, had been ignored so far.

Molecular line observations confirm that a statistical study of 2MASS data can lead to the identification of massive dark clouds in the Outer Galaxy.

G111.80+0.58 is a massive dark cloud complex (M_{cores} > 3000 M$_\odot$) and possibly the first identified Outer Galaxy object resembling IRDCs.

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