Time Allocation Committee for
Centro Astronómico Hispano Alemán (CAHA)
c/o MPI für Astronomie
Königstuhl 17
D-69117 Heidelberg / Germany

Application No.	H06-3.5-024
Observing period	H 2006
Received	14.03.06 19:00

APPLICATION FOR OBSERVING TIME

from [ ] Germany [X] Spain [ ] other

[X] Autumn period beginning of July - end of December, acceptance till March 15.

[ ] Spring period beginning of January - end of June, acceptance till September 15.

1. Telescope: 2.2-m [ ] 3.5-m [X]

2.1 Applicant

Dr. Mario **Tafalla**	Observatorio Astronómico Nacional
Name	Institute
Alfonso XII, 3.	E-28014 Madrid
street	ZIP code - city
Spain	m.tafalla@oan.es
country	e-mail

2.2 Collaborators

João Alves	CAHA
name(s)	institute(s)
Jonathan Foster & Jaime Pineda	Harvard-Smithsonian Center for Astrophysics
name(s)	institute(s)

2.3 Observers

Jonathan Foster	Jaime Pineda
name	name

CAHA points out that by specifying the names under item 2.3 it is obligatory to also send out these observers to Calar Alto. Correspondence on the rating of this application will be sent to the applicant (P.I.) as quoted under 2.1 above.

3. Observing programme and method: Category: C

Title : **Tracing the Density Profile of Cores in Perseus**

Abstract : Following up on a discovery made in our successful prior proposal, we propose to finish obtaining high-resolution near-IR extinction maps of all dense regions outside of the clusters in Perseus and at the same time calibrate a new method for obtaining arcsecond-resolution density maps. This work is part of the COMPLETE (COordinated Molecular Probe Line Extinction Thermal Emission) Survey of Star-forming Regions which is fully-sampling the density, temperature, and velocity structure of Perseus. The high-resolution views of the density structure in combination with COMPLETE molecular observations will allow us to study chemical depletion in a large sample of cores, while broad field of view of OMEGA 2000 will show us how dense cores form out of the surrounding turbulent cloud.

4. Instrument: OMEGA 2000 Method: Photometry

5. Brightness range of objects to be observed: from 18 to 20.25 K-mag

6. Number of nights:

applied for			already awarded	still needed
4			none	none
no restriction	grey	dark		

7. Optimum date range for the observations: .... 23.10.06 – 21.11.06
Usable range in local sideral time LST: .... 23:00h – 9:00h

Astrophysical context

The density structure of cores and their environs allows us to see how coherent structures form out of a turbulent cloud and, in combination with molecular observations, trace the depletion of molecules over a wide range of densities. Obtaining the density structure is not easy. Using dust continuum emission relies on assumptions about temperature and emissivity; both are usually taken to be constant, but this is not always a good assumption. Furthermore, temperature variation along the line of sight confound accurate column density measurements [8], so other methods are required.

The best measure of column density to date is extinction mapping, which is simple and works over a broad range of densities (A_v = 1-40). We look along a line of sight, measure the reddening of the background stars, convert to extinction, and learn the dust column density. The near IR (J,H, and K) is ideal for this purpose, since most stars have no intrinsic color in these bands and we can interpret a reddened color without a detailed stellar type. The resolution of an extinction map is proportional to the density of stars used in its construction. For fields at low galactic latitude, the NICER (Near Infrared Color Excess method Revisited) method can achieve a resolution of 10″ [5] but further off the plane, the under-sampled background of stars limits a map's resolution to arcminute scales. This is the case in the Perseus molecular complex where the COMPLETE (COordinated Molecular Probe Line Extinction and Thermal Emission) collaboration has finished Phase I (large, relatively shallow) surveys (Ridge et al. 2006), which provide invaluable context for further studies of this cloud.

Observations obtained under our previous proposal (F05-3.5-054) have suggested a new approach to obtain high-resolution density maps at higher galactic latitudes. The phenomenon of "cloudshine", was shown to be diffuse galactic radiation reflecting off dust within dark clouds [100]. These beautiful images (see figure 1) show features at ultra-high resolution: with sufficient signal-to-noise, the only limit is seeing (0.6-0.7″). As the illumination is roughly isotropic, and near-infrared dust grain optical properties are insensitive to dust size variation which may occur inside cores, the qualitative impression of "seeing" the cloud's structure is convertible to a quantitative, unbiased estimator of column density. This has been demonstrated by theoretical models in work inspired by our observations [6].

Immediate aim

The immediate aims of this program are thus twofold – to continue the survey of dense cores in Perseus started in our previous proposal, and to prove and calibrate this new method of mapping column density at arcsecond resolution. The exact same set of observations provide both these important benefits. In figure 3 we show three views of the dark cloud L1451: first the 5′ resolution extinction map possible from the 2MASS point source catalog (part of Phase I of COMPLETE); next, a column density map from last year's Calar Alto observation of this region, where we were able to push down to 1′ resolution; finally, a rough column density map made from cloudshine, where the column density is taken as a linear function of K-band surface brightness. Stars have been masked out, and the diffuse emission smoothed to 15″ for higher signal-to-noise and to partially overcome the effect of self-sky subtraction (we had not anticipated extended emission). A more sophisticated method fitting all three colors is suggested in Padoan et al. [6] and is much better at high density. New observations are required to use this method as we need higher signal-to-noise J-band images (our pervious observations in this band were short), and we must avoid the distorting effects of self-sky by observing these fields as extended objects, chopping to low-column density regions.

The high-resolution extinction maps will also be very useful in two ongoing projects, since 1arcminute, is comparable to COMPLETE ^{13}CO and 850 μm observations. Work currently underway is showing that one's estimate of whether cores are bound depends in detail upon whether one uses ^{13}CO or extinction-based masses. Peaks identified in the 850 μm map are sometimes coincident with extinction peaks (as in L1455), but sometimes not (B1-east). The difference must lie in a mismatch between the scales. We will cover all the peaks identified in these regions and study which regions are really smooth, which have sharp peaks, and whether the morphology of the surrounding gas differs between these cases.

Previous work

Prior work has studied the physical conditions present at the birth of stars. Tafalla et al. [10] have characterized the physical structure and chemical composition of two starless cores. Tafalla & Santiago [9] have found evidence of the first starless core with essentially no molecular depletion of ^{18}CO at high densities. Possibly this core is too young for molecules to have had time to deplete. Both works relied on 1.2 mm continuum observations to derive the densities of the cores; the methods suggested here provide a more robust profile. The NICE algorithm has been applied succesfully to several cores ([1], [2]), demonstrating that the basic structure of many dark clouds cores is well characterized by a Bonnor-Ebert sphere. Foster & Goodman [100] modeled the cloudshine in our previous Calar Alto images, suggesting this new column density approach.

Layout of observations

Phase II of COMPLETE targets the dense cores in Perseus outside the main clusters (where an embedded population limits extinction mapping). Here we cover all the 850 μm peaks in the south-west; these locations also have N_2H^+ observations. A range of densities and positions within the cloud is sampled to test the the cloudshine method. B1-east and L1455 are covered in single frames, while a mosaic of 7 slightly overlapping frames covers B1 (see figure 2). We will chop to low-column density regions where there is no flux from cloudshine to do sky-subtraction. One control field at the edge of the complex will complete our knowledge of the intrinsic background stellar colors.

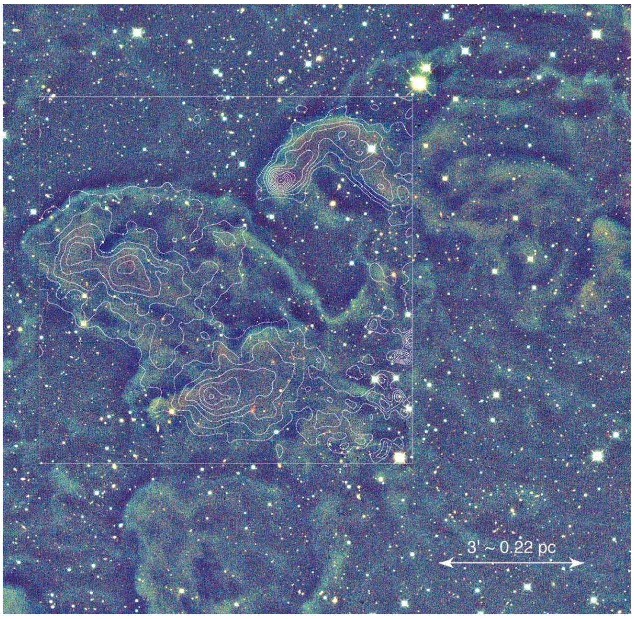

Figure 1: L1451 shown in false color (with J = blue, H = green, K = red). Overlain are 1.2-mm dust continuum maps from Tafalla et al. [11], showing that density seems to correlate well with color.

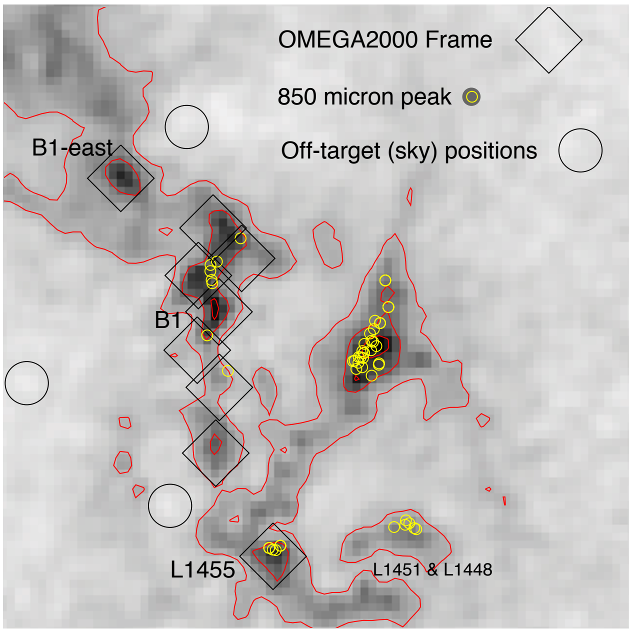

Figure 2: Our targets in Perseus, shown on our 2MASS-based extinction map with contours at A_v of 3, 6, and 9. L1451 and L1448 in the south were covered (along with a large mosaic of B5 in the north) in previous observations. The dense cluster, NGC 1333, is not amenable to extinction mapping due to a large population of foreground or embedded objects. Outside of these regions, we can cover all the dense features as identified in the broad extinction map and the 850 μm map of Kirk et al. [4].

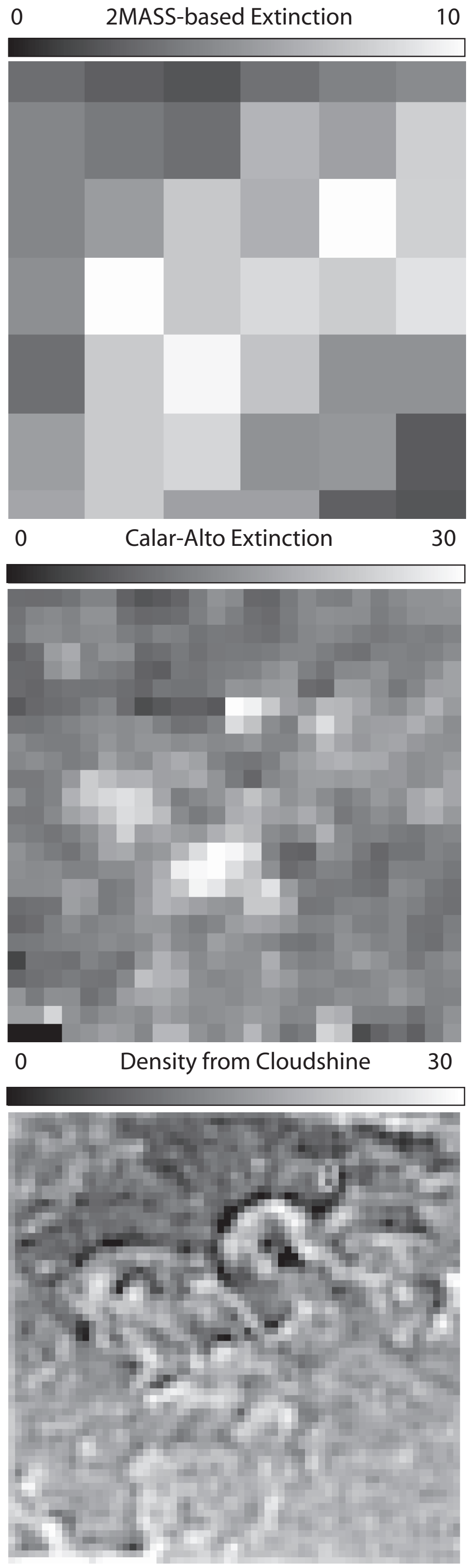

Figure 3: The quest for increased resolution. At top, L1451 in an extinction map with the 2MASS point-source catalog ($5'$, covering A_v=0-10). In the middle, an extinction map derived from our observations last year at Calar-Alto ($1'$, covering A_v = 0-30). At the bottom, the K-band image of these region with the stars removed, smoothed to $15''$, and scaled to match the extinction map. This inadequately reproduces the column density. Dark edges from self-sky subtraction are still visible, and the densest features are subdued. Our proposed observations in combination with a better algorithm [6] will solve both problems.

9. Objects to be observed

(Objects to be observed with high priority should be marked in last column)

Designation	α (2000)	δ (2000)	Av	priority
Pers-1	$03^h\,36^m\,24.^s807$	$+31^\circ\,10'\,40.16''$	8	1
Pers-2	$03^h\,27^m\,36.^s158$	$+30^\circ\,10'\,51.98''$	7	1
Pers-3	$03^h\,32^m\,14.^s810$	$+30^\circ\,45'\,11.46''$	3	2
Pers-4	$03^h\,33^m\,54.^s389$	$+31^\circ\,17'\,42.94''$	6	1
Pers-5	$03^h\,31^m\,14.^s914$	$+30^\circ\,40'\,45.77''$	3	2
Pers-6	$03^h\,30^m\,16.^s575$	$+30^\circ\,24'\,11.88''$	5	1
Pers-7	$03^h\,32^m\,53.^s441$	$+31^\circ\,16'\,15.75''$	4.5	1
Pers-8	$03^h\,32^m\,27.^s379$	$+30^\circ\,58'\,49.78''$	4	1
Pers-9	$03^h\,33^m\,25.^s064$	$+31^\circ\,03'\,20.22''$	6	1
control-1	$03^h\,35^m\,40.^s533$	$+31^\circ\,40'\,52.46''$	0.7	1
control-2	$03^h\,34^m\,58.^s621$	$+30^\circ\,01'\,31.14''$	1	2
control-3	$03^h\,30^m\,14.^s807$	$+30^\circ\,03'\,11.07''$	1.3	1

10. Justification of the amount of observing time requested:

OMEGA 2000 on the Calar Alto telescope provides an ideal site for infrared-extinction surveys. The camera's extremely large field of view, combined with a fair size telescope provides both the spatial coverage and depth necessary to study the density structure of cores as they collapse out of their surroundings.

With a FOV= $15.4' \times 15.4'$ we plan a total of 9 science pointings (see Figure 2) and 1 control fields. The method that will be used to derive infrared extinction relies strongly on the observation of these control fields, from which we derive the normal stellar background and any extinction that is foreground to the entire complex. We place our control field at the edge of the complex where we expect there is no gas and dust, as evidenced by a lack of CO emission and zero extinction in the 2MASS extinction map. Previous observations obtained two control fields to the north and south of Perseus region, so only one additional control field will be observed to the east to check for any variation.

The number of stars observed limits the resolution of the map. From our experience with the 2MASS extinction map we discovered that to make a map with no holes after we spatially smooth required an average of ≈ 12 (stars)/(pixel), a criteria we adopt here.

The limiting factor in dense cores at this galactic latitude is seeing enough stars in H (which is, at an A_V of 10, 0.6 magnitudes dimmer than K). We aim for at least $1.5'$ resolution which corresponds to $\approx 0.10\,$pc at the distance of Perseus. To achieve the necessary stellar density, the SKY4 model (Cohen 1994) predicts we will have to reach a magnitude of H ≈ 21 (20.4 mag with an A_V of 10 in the densest regions). This model prediction was borne out by our prior observations in this region, which were complete H of $\approx$ 21 and enabled an extinction map with 1 $'$ resolution. This was reached in 45 minutes of of exposure time. Since we will be observing these regions as an extended source, we will have to slew frequently to sample the sky at nearby low-column density regions, decreasing our efficiency. We estimate 40% efficiency in this mode, thus needing 112 minutes.

A similar stellar density in K is reached a 20.25 mag, which can be reached in 37 minutes of integration, or 92 minutes of observing. At regions of high extinction we will see few stars at J, but the third color component is crucial to our cloudshine maps. We plan to reach a J of 21 mag in 10 minutes of integration time, or 25 minutes of observing. In total then, a science frame will require about 4 hours of observing (accounting for overhead).

Our source is observable (above an airmass of 2) for 10 hours during the optimum time requested in this proposal. Our 9 science frames and one control field will thus require 4 nights.

11. Constraints for scheduling observations for this application:

12. Observational experience of observer(s) named under 2.3:
(at least one observer must have sufficient experience)

Jonathan Foster carried out the deep near-infrared observations of Perseus under our previous project, using OMEGA 2000 on the 3.5-meter. He and Jaime Pineda have also made deep near-infrared observations at CTIO with ISPI to produce extinction maps in Ophiuchus.

13. Calar Alto runs (preferably during the last 3 years)
and publications resulting from these

Telescope	instrument	date	nights	success rate	publications
3.5m	OMEGA 2000	Jan 05	4	75%	Foster & Goodman (2006) [100]

14. References for items 8 and 13:

[1] Alves, J., Lada, C. J., Lada, E. A., Kenyon, S. J., & Phelps, R. (1998): *Dust Extinction and Molecular Cloud Structure: L977*, ApJ **506**, 292

[2] Alves, J. F., Lada, C. J., & Lada, E. A. (2001): *Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight*, Nature **409**, 159

[3] Cohen, M. (1994): *Powerful model for the point source sky: Far-ultraviolet and enhanced midinfrared performance*, AJ **107**, 582

[4] Kirk, H., Johnstone, D., & Di Francesco, J. (2006): *The Large and Small Scale Structures of Dust in the Star-Forming Perseus Molecular Cloud*, astro **arXiv.org:astro-ph/0602089**, accepted to ApJ.

[5] Lombardi, M., & Alves, J. (2001): *Mapping the interstellar dust with near-infrared observations: An optimized multi-band technique*, A&A **377**, 1023

[6] Padoan, P., Juvela, M., & Pelkonen, V.-M. (2006): *High-Resolution Mapping of Interstellar Clouds by Near-Infrared Scattering*, ApJ **636**, L101

[7] Ridge, N. A., Di Francesco, J., Kirk, H., Li, D., Goodman, A. A., Alves, J. F., Arce, H. G., Borkin, M. A., Caselli, P., Foster, J. B., Heyer, M. H., Johnstone, D., Kosslyn, D. A., Lombardi, M., Pineda, J. E., Schnee, S. L., & Tafalla, M. (2006): *The COMPLETE Survey of Star-Forming Regions: Phase I Data*, **arXiv:astro-ph/0602542**, accepted to AJ.

[8] Schnee, S., Bethell, T., Goodman, A. (2006): *Estimating Column Density in Molecular Clouds with FIR and Sub-mm Emission Maps*, astro **arXiv.org:astro-ph/0602286**, accepted to ApJL.

[9] Tafalla, M., Santiago, J. (2004): *L521E: The first starless core with no molecular depletion*, A&A, **414**, L53-56

[10] Tafalla, M., Myers, P.C., Caselli, P., Walmsley, C.M. (2004): *On the internal structure of starless cores I. Physical conditions and the distribution of CO, CS, N_2H^+, and NH_3 in L1498 and L1517B*, A&A, **416**, 191-211

[11] Tafalla, M. et al. (2006): in prep.

[100] Foster, J. B., & Goodman, A. A. (2006): *Cloudshine: New Light on Dark Clouds*, ApJ **636**, L105

15. CAHA does not cover costs of the observing run. It is the responsibility of the applicant(s) to raise the money for the travel to Calar Alto and expenses during the observing run.

    Consumables needed in larger quantities will be charged to the applicant(s).

    Furthermore the applicant(s) should consult our web page with the "Guidelines for Visiting Astronomers":

    http://www.caha.es/visast.html

16. Members of institutes of the Rat Deutscher Sternwarten (except Max Planck institutes) may apply for travel funding at the DFG with reference to this application and the letter granting observing time.

    Should observing time be granted is it planned to apply for DFG funds? yes [ ] no [X]

Tolerance limits for planned observations:

maximum seeing:	2″	**minimum transparency:**	50%	**maximum airmass:**	2
photometric conditions:	yes	**moon: max. phase / ∠ :**	1/20°	**min. / max. lag:**	/ nights

- ● **3.5m**
  - ● Prime focus
    - ☐ LAICA
    - ● OMEGA 2000
  - ☐ Cassegrain focus
    - ☐ TWIN spectrograph
      - ☐ beam splitter
      - ☐ mirror
      - blue channel — grating:
      - red channel — grating:
    - ☐ OMEGA Cass → ☐ without adaptive optics / ☐ with adaptive optics
    - ☐ MOSCA
    - ☐ PMAS → ☐ PPAK / ☐ LensArray
    - ☐ private instrument →

- ☐ **2.2m**
  - Coudé focus temporarily not available
  - ☐ Cassegrain focus
    - ☐ CAFOS
      - ☐ polarizer
      - ☐ Etalon
    - ☐ MAGIC
      - ☐ 1.″6/pixel
      - ☐ 0.″66/pixel → ☐ Grism R270
    - ☐ FOCES
    - ☐ BUSCA
    - ☐ private instrument →