2- The Science Case

We have selected tree main science drivers: black holes and their accretion disks, molecular evolution and its connection to astrobiology, and the Galactic spiral structure. There are several active and competent researchers in Brazil and Argentine, working on each of these areas, who are interested in using LLAMA. Hence these programs will naturally represent an important parcel of the observing time. In addition, these are areas in which LLAMA will be competitive compared to other radiotelescopes, so that we can expect a production of results of great scientific impact. The previously mentioned science cases will benefit from both single dish and interferometry observations. Other science cases will be only shortly mentioned.

The proximity of ALMA and similarity of the radio bands of the two observatories will benefit the LLAMA users in two manners. Firstly, LLAMA will provide experience in mm/sub-mm astronomy and knowledge of the environment of the objects for Brazilian and Argentinean astronomers, and will help to prepare competitive proposals for ALMA. Secondly, when important discoveries will be made by ALMA, it is probable that it would be desirable to obtain observations with better angular resolution by a factor of ten, and for that LLAMA will be an essential partner. It is predictable that this synergy with ALMA will “per se” generate results of great impact.

Another point to be mentioned is that LLAMA will be the seed for the Latin-American effort in VLBI experiments. For instance, it is intended to install a receiver in band 1 of ALMA (45 GHz). This will make possible to do VLBI experiments with other radiotelescopes like the Itapetinga antenna in Brazil (a 2000 km baseline), the radiotelescope being built by the Chinese Academy of Science in San Juan, Argentina, and other radiotelescopes, to observe the SiO maser at 43 GHz (found in stellar envelopes), or the methanol maser at 44 GHz (associated with star-forming regions). With the Sicaya 30 m antenna in Peru, 22 GHz masers could be also explored.

In future, when an additional antenna of the LLAMA system will be installed at about 200 km to the South of San Antonio de los Cobres (SAC), near Macon, the millimetric array Chajnantor-SAC-Macon- will be unique in the world because of the high altitude and low water content of the atmosphere.

1) LLAMA as a laboratory for fundamental astrophysics of black holes and accretion disks

The Supermassive black hole at the Galactic center, identified with the radio source Sagittarius A*, is the nearest of such objects. As a consequence, it has the largest apparent event horizon of any known black hole candidates (~10 μas), and it deserves many different types of observations. One of the challenges of present days, which stimulates a competition between different groups in the world and is expected to produce results of strong impact, is to observe the "shadow" of the black hole, which would be the final proof that the black hole indeed exists and the confirmation of one of the predictions of General Relativity. See for instance the plans to build several radio-telescopes only for this target by Miyoshi et al. (2007) and the Science White Paper submitted to the Decadal Review Committee (Doeleman et al. 2011). The possibility of seeing this shadow with the high spatial resolution of VLBI experiments was discussed by Falcke, Melia & Agol (2000). They predict that the angular size of the shadow is about 30μas, which would require millimetric VLBI with baselines of the order of 10^3 km to be observed. Possibly these observations will already have been made when LLAMA enters in operation, although the possibility of LLAMA becoming a partner is not excluded.

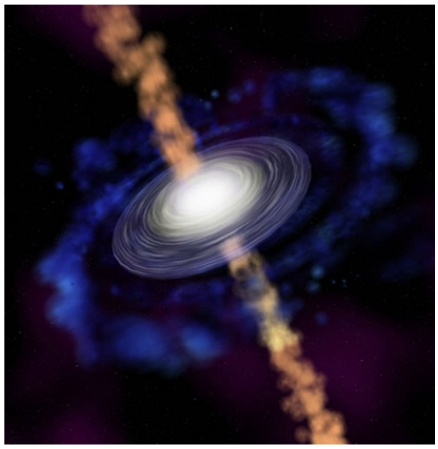

***Figure 2-1**. Artistic view of accretion disk around a black hole, and its jet*

VLBI observations already inferred a size limit of 37 µas on the 1.3 mm emission, with a baseline between the JCMT in Hawaii and the SMT in Arizona (Doeleman et al. 2008). However, Doeleman et al. (2009) emphasized that observations with more baselines are needed, and mentioned the difficulty of performing VLBI experiments between North America and Europe, since there is no mutual visibility of Sgr A*, except for approximately 1 hr of overlap above 10° elevation on the baseline between Pico Veleta (Spain) and Large Millimetric Telescope (under construction in Mexico). Broderick (2011) also discusses the need for more antennas for phase closure studies in observations of Sgr A*.

There are several reasons to observe Sgr A* with LLAMA at millimeter wavelengths; 1) its spectrum peaks in the millimeter bands, 2) interstellar scattering, which varies as λ^{-2}, dominates over intrinsic source structure at longer wavelengths, 3) the transition from optically thick to optically thin emission occurs near λ= 1 mm (Doeleman et al. 2001), and 4) millimeter wavelengths permit observations by the technique of VLBI with the lowest λ/D (largest resolution).

There will be also a significant contribution to the understanding of the physics of Sgr A* from variability observations with LLAMA. The rapid NIR and X-ray variability of Sgr A* exhibits substructures on minute timescales, implying that the source of variable emission in these bands is localized in sub-horizon scales. Flaring at mm wavelengths has been reported in the direction of Sgr A*, and has been interpreted in terms of orbiting hot spots in the accretion disk (Doeleman et al., 2009). However, there is a debate in the scientific community concerning the nature of this variability; other possibilities include jet outflows and magnetohydrodynamic instabilities in the accretion process. Simultaneous multiwavelength observations have to be performed to confirm the delay of about 20 min which has been observed between 43 GHz and 22 GHz (Yusef-Zadeh et al, 2008). We could think in terms of single dish observations at different frequencies (like 45 GHz at Itapetinga, 100 GHz at LLAMA and 250 GHz at APEX). However, it is possible that single dish observations would not be sufficient to clarify the question of the delays, since different components in the beam of a single dish can present variations. It would then be preferable to look at variability with short distance VLBI, in order to separate the central source. VLBI experiments between LLAMA, Itapetinga, and a third antenna (reactivated SEST? Chinese-Argentinean antenna near San Juan?) at 45 GHz could perform such measurements.

Finally, polarization studies of the emission of Sgr A* should be done, to distinguish between different emission mechanisms. The polarization of the flares is of particular importance. Since LLAMA will be polarization-oriented, it will be easy to perform single dish observations of it.

Although Sgr A* is intended to be a driver of the science to be made with LLAMA, even more massive black holes in AGNs cannot be neglected. The spectral energy distribution of these objects presents two maxima, the low frequency emission shows a peak at IR-soft X-ray wavelengths, which is attributed to synchrotron radiation, and the high frequency emission that peaks at γ-rays is attributed to the Inverse Compton process, possibly from the same photons produced by synchrotron radiation (SSC). The position of these peaks is correlated with the bolometric luminosity of the AGNs, as shown in Figure 2-2, obtained from a mean of 126 objects by Fossati et al. (1998). The frequency interval between the two vertical lines is now covered by the recently launched FERMI observatory (http: //fermi.gsfc.nasa.gov/). Part of the seed photons that produce this high energy emission have millimeter wavelengths and could be observed with LLAMA.

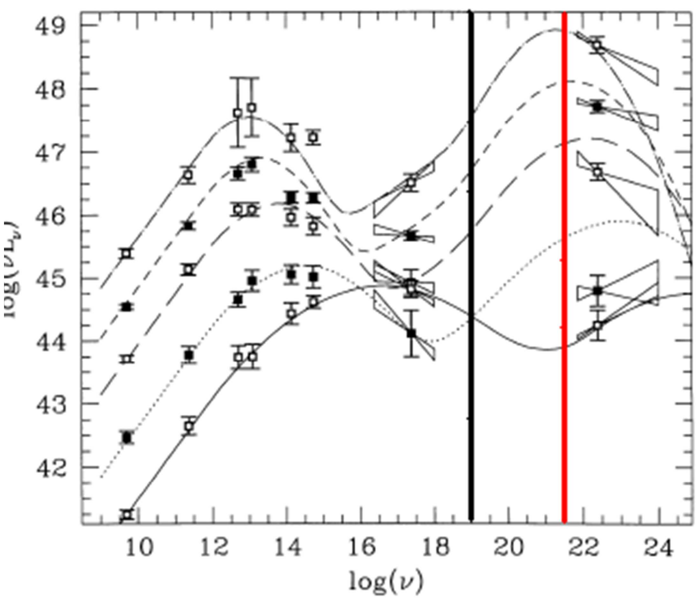

Figure 2-2*. Average spectral energy distribution for a blazar sample binned according to radio luminosity. The overlaid curves are analytic approximations (Fossati et al., 1998*).

Another aspect of the AGN emission is its variability at all wavelengths. The brightest objects at radio wavelengths (quasars and blazars) present jets, with components moving away from the core sometimes at superluminal velocities. These components are attributed to shocks propagating with relativistic velocities along jets that form small angles with the line of sight. When the shocks are generated, close to the central engine, the size of the emitting region is very small and optically thick at radio frequencies; the synchrotron emission is detected only at optical-soft X-ray frequencies, and the Inverse Compton emission at γ-rays. As the shocks propagate, the electrons loose energy first by Inverse Compton emission, afterwards by synchrotron emission and finally by adiabatic expansion. As the size increases, the source becomes optically thin and can be detected at millimeter and radio wavelengths. The delay between the start of variability at different wavelengths (which can be of several months) gives important information about the physical conditions of the shock and of the underlying jet. Its measurement is nowadays restricted to a few dedicated radiotelescopes, all of them in the northern hemisphere. The possibility of having coordinated observations between LLAMA, at millimeter wavelengths and Itapetinga at 7 mm can make great contribution to this field.

The molecular dusty torus that surrounds the accretion disks and the supermassive black holes can also be studied with LLAMA. These structures present generally warps, and in general, their orientations do not coincide with that of the radio jets. This is a matter of great interest because it can be related to the Bardeen-Petterson torques, produced by a rotating black hole on a viscous accretion disk, predicted by the Theory of General Relativity (Caproni et al., 2006).

Nearby accretions disks with jets will also be targets for VLBI observations, like those of T Tauri stars and galactic microquasars. Although smaller and less energetic than those around massive black holes, protostellar accretion disks and jets are ideal laboratories to explore the acceleration mechanism of jets and the physics of accretion disks in general, because of their proximity. As supermassive black holes in the center of active galaxies expel the excess of accreted matter and energy back into the intergalactic environment through a narrow supersonic jet, protostars also eject part of the matter they accrete from the cloud progenitor back into the interstellar medium. Millimetric VLBI observations of protostellar disks and jets will allow to finally test the predicted ubiquitous jet launching mechanism based on a magneto-centrifugal process which was proposed by Blandford and Payne (1982) more than three decades ago. The detection of rotation and the inner disk structure at the jet launching regions will probe this mechanism as well as the universal acceleration and heating processes in jet/accretion phenomena predicted by analytical modeling and numerical magneto-hydrodynamical simulations (e.g., de Gouveia Dal Pino et al. 2010, and references therein).). Figure 2-3 illustrates the results of MHD simulations of an accretion disk of a newly born star, without jet.

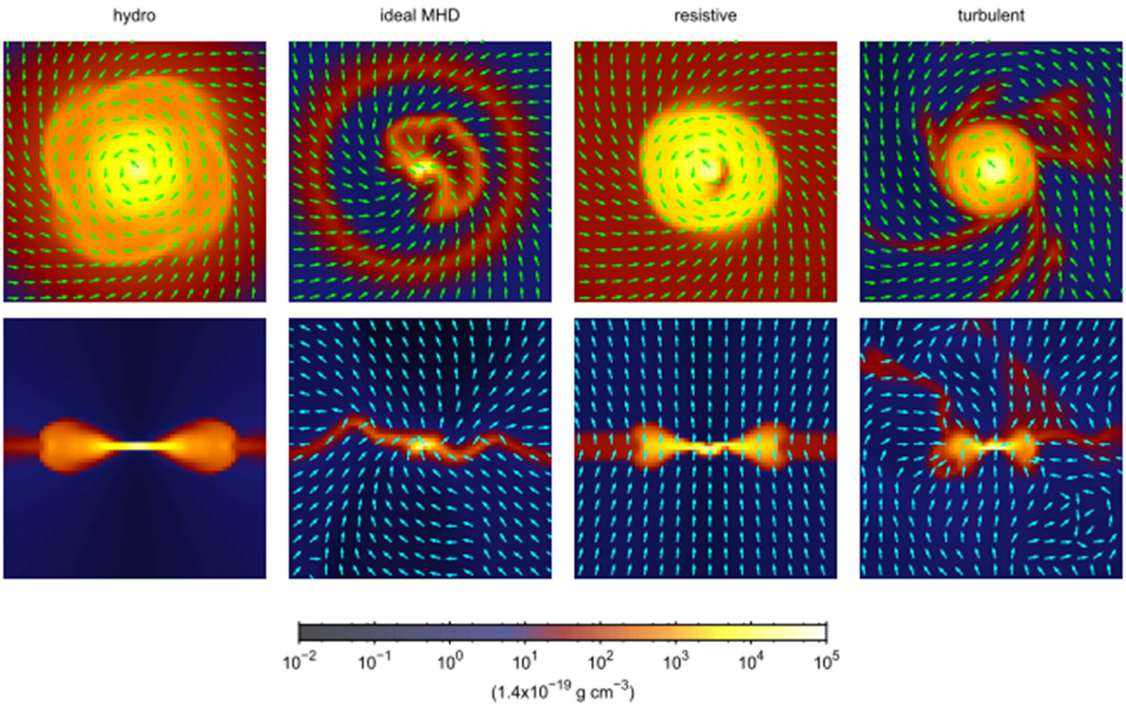

Figure 2-3. *Models of disk formation around a protostar (from Santos-Lima et al. 2011). Face-on (top) and edge-on (bottom) density maps of the central slices of collapsing disk models at a time t ≈ 0.03 Myr. Arrows in top panels represent the velocity field direction, in the bottom panels the magnetic field direction. From left to right rows: (1) a pure hydrodynamic rotating system, (2) ideal MHD model, (3) MHD model with an imposed resistivity 10^3 times larger than the Ohmic resistivity, (4) MHD model with turbulence injected from t = 0 until t=0.015 Myr. The MHD models have initial vertical magnetic field with intensity B_z = 35 µG. Each image has a side of 1000 AU.*

Finally, a useful single dish program will be to monitor the spectra of extragalactic H_2O megamasers associated with active nuclei of galaxies. The emission is usually divided in 3 main spectral peaks, and it has been shown in several cases that the sub-structures of the central peak present a secular drift in velocity (eg. Greenhill et al. 2009). The central peak is associated with the material of the accretion disk passing in front of the black hole, and the velocity drift is due to the centripetal acceleration of the material; measuring the drift is a step towards determining the mass of the black hole. It will be interesting to determine precisely the mass of a number of central black holes of active nuclei to test the relation between the mass of the black holes and the host galaxy mass (eg. Target et al. 2011).

2)- Molecular evolution and astrobiology

About 160 molecular species have been detected up to now in the interstellar space, with complexity reaching 70 atoms (Fullerene, C_{70}, detected by J. Cami et al., 2010). These molecules are found in molecular clouds located primarily in the spiral arms of the Galaxy, in envelopes of AGB (Asymptotic Giant Branch) stars, in planetary nebulae and in comets. Most of these molecules are organic as they contain Carbon atoms. A particular type of organic molecule, the polyaromatic hydrocarbons (PAHs) have been detected in distant galaxies up to z = 2 (e.g., Elbaz et al. 2005) and in protocluster galaxies up to z ~4 (Riechers et al. 2010) using the ISO and SPITZER satellites. This shows that this kind of molecule is rather abundant in the Universe.

Other common carbon-reacting elements in the interstellar medium are Hydrogen, Oxygen and Nitrogen. A large fraction of the detections of molecules have been made in the mm/sub-mm region of the spectrum, where they have rotational and vibrational transitions. While some molecules are familiar ones, like benzene or acetone, others like linear chain molecules (cyanopolyynes) HC_9N, $HC_{11}N$ and $HC_{13}N$ were first detected in the interstellar medium and only later synthesized in laboratory. Certainly many complex molecules do exist in space, but have not been detected since their transition frequencies are not known, as they are difficult to predict through the use of quantum mechanics. Indeed, many unidentified lines appear in the mm/sub-mm region. Figure

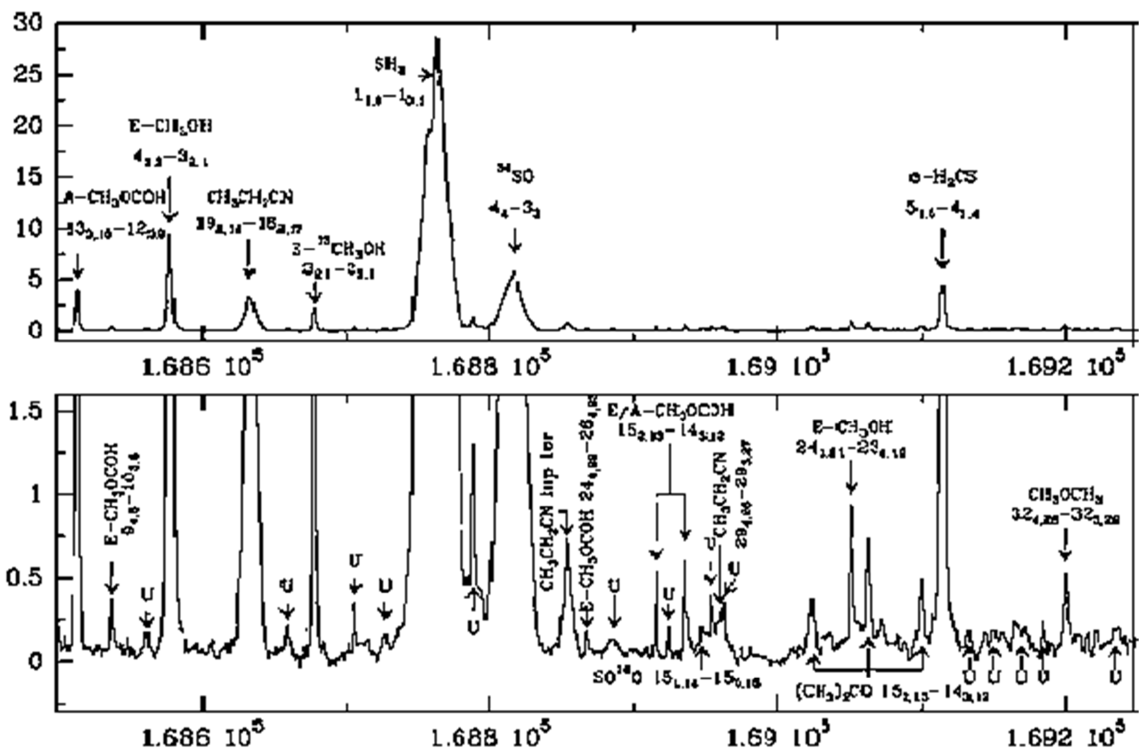

Figure 2-4. *Spectrum of molecular emission from the Orion Kleiman-Low nebula by Tercero et al.(2010). Only a portion of the spectrum is shown, around 169 GHz. The same region is shown for two scales of intensity (in Kelvins). This illustrates the large number of unidentified molecular lines (indicated by letter U).*

2-4 illustrates the result of spectral observations towards the Orion KL nebula at 2mm (Tercero et al., 2010). The U letter indicates lines that are unidentified.

The formation of molecules by direct collisions of atoms is a low probability mechanism. It is generally accepted that chemical reactions on the surface of interstellar dust grains play a major role in the formation of molecules and on their evolution towards more complex compounds. Simple molecules or atoms can stick to the surface of grains and stay there for a sufficiently long time to meet another molecule and to react and form a more complex one. The grain is able to absorb the heat of such reactions, avoiding the immediate re-dissociation of the new molecules. Such molecular reactions occur near the center of cool and dense clouds, where very low temperature (10-20K) prevails, and where the dust grains are shielded from external radiation. Interestingly, these are the same conditions which favor star formation. In other words, stars and their planetary systems are born in a molecular environment. Going back to the molecular evolution, cosmic rays are the only energetic particles which are able to penetrate dense clouds. Eventually a cosmic ray can reach the molecular mantle of a grain causing it to evaporate, ejecting molecules into the gas phase, and prompting them to stick to other nearby grain.

One of the goals of research on molecular evolution is to examine the content of different molecular clouds, and to understand how the complexity of molecules evolves. Clouds containing only simple molecules can be considered to be "young", while clouds harboring more complex compounds probably took several million years reach their present chemical composition. However, the evolution is always fast, since molecular clouds are never very old; the estimated lifetime of a molecular cloud is about 20 Myr. Understanding what molecules can be assigned to a given stage of evolution of a certain cloud will help to undestand which reaction paths are necessary to form them. The comparison of spectra of different clouds could give us clues to the nature of non-identified lines. Another interesting subject of studies is molecules containing isotopes of Carbon or Oxygen, like C^{13}, O^{17}, and others. A number of authors claim that there is a "fractionation" of isotopologues, for instance with heavier molecules concentrated in the innermost regions of the clouds. Such conclusions must be regarded with suspicion, as the effect could be simply due to optical depth (rarer isotopes are optically thinner and easier to observe in very dense regions).

The strong winds of mass-losing AGB stars are believed to be the main source of interstellar grains, since their signature are evident in the energy distribution of the envelopes of those stars. The grains survive in the interstellar medium and are gathered together when the gas starts to concentrate to form molecular clouds. There are two very distinct types of AGB stars, from the chemical point of view: the oxygen-rich and the carbon-rich ones, which produce different types of grains (oxygen-rich silicates and iron oxides in the first ones, graphite and PAH molecules, in the second ones). A carbon-rich interstellar medium seems to be widespread, constituting an "aromatic world", where poly-aromatic hydrocarbons were estimated to be on top abundance scores just after H_2 and CO. Although the PAHs only have spectral bands in the near-infrared, but not in the mm/sub-mm range, they can possibly still be investigated at the LLAMA wavelengths through a new mechanism of continuum emission. Recent results from the Planck collaboration (2011) estimate that spinning dust grains, mostly constituted of PAH molecules, are responsible for 30% of the continuum observed at 30 GHz in the molecular phase of the interstellar medium of the Galaxy.

IRC10216 is a prototype of carbon-rich AGB stars; it is nearby but difficult to observe in the visible, and presents a large variety of carbon-rich molecules. One of the last detected is FeCN (Zack et al., 2011). The dust grains formed in similar envelopes seed the growth of mantles and the future chemical evolution of molecular clouds. It is still unclear if seeds of different origins (oxygen-rich or carbon-rich stars) can ever impact the evolution of a molecular cloud. This emphasizes the need for paying attention to their nearby environment, like the presence of stellar winds or supernovae remnants (which are sources of cosmic rays). It would not be surprising if the metallicity of the ISM had an effect on the molecular evolution of clouds.

There is a growing belief that molecules that constitute the building blocks of life were more easily assembled in the interstellar space than on the Earth, and that the Earth was populated by such molecules by the bombardment of comets. The comets are considered as reservoirs of the molecular content of the primitive dust cloud in which the solar system was originated. The search for large molecules of biological importance in the interstellar medium, conducted for instance by Hollis and his group (2004a, 2004b, 2006a, 2006b), have led to the detections of interstellar aldehydes like propenal (CH_2CHCHO) and propanal (CH_3CH_2CHO), simple aldehyde sugars like glycolaldehyde (CH_2OHCHO), the first keto ring molecule to be found in an interstellar cloud, cyclopropenone (c-H_2C_3O), the organic imine (chemical compound containing a carbon–nitrogen double bond) ketenimine (CH_2CNH) (Lovas et al. 2006), and acetamide (CH_3CONH_2), and cyclic molecule ethylene oxide (c-C2 H4 O), a precursor to the formation of the sugar phosphates which comprise the backbone of our molecular genetic structure. Finally, urea $(NH_2)_2CO$, illustrated in Figure 2-5, of significant role in prebiotic chemistry, was detected at 1mm (Kuo et al., 2010).

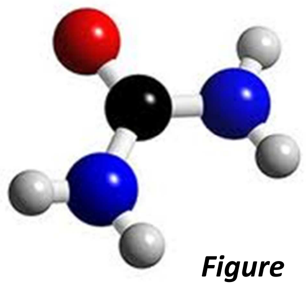

Figure 2-5*. Urea*

The research on molecular species and their evolution is mainly a program for single dish observations, since usually the molecular clouds have relatively large sizes. LLAMA will be competitive due to its excellent site at almost 5000 m altitude, and to its large frequency coverage and low-noise receivers. One of the most important molecular clouds, Sgr B2, is only seen near at low elevation from the Northern Hemisphere, which increases the atmospheric absorption and system noise. Maps of different molecular clouds in the Southern Hemisphere, and in particular of the Magellanic Clouds, which are examples of low-metallicity ambients, will help to elucidate important factors that can have an influence on the molecular chemistry.

New species will be discovered by sensitive and methodical surveys. The identification of new species is often time consuming, since ideally the detection of several transitions of the same molecule, in different frequency bands, is required. In the case of the above mentioned urea, eight weak lines were identified, blended with nearby transitions. The advance the astrochemistry field will benefit from a comprehensive inventory of the existing molecular species.

The interest for astrobiology has recently grown in Brazil, as shown for instance by the creation of the Research Unit in Astrobiology by USP (NAP-Astrobio), the first International School of Astrobiology (FAPESP 11/50124-2), and the installation of an Astrobiology lab at the Abrahão de Morais Observatory of USP. Research groups in Brazil are performing experiments which consist in bombarding ices (simulating the mantles of dust grains in space) with heavy ions (de Barros et al., 2011) and identifying the generated chemical species. Ices have also been submitted to soft X-rays using the Brazilian synchrotron light source (LNLS) (Andrade et al., 2010, Pilling et al., 2011) for the same purpose.

A class of astrobiologically interesting molecules is constituted by heterocyclic compounds. In terrestrial biochemistry, the heterocyclic pyrimidines (cytosine, thymine, and uracil) and purines (adenine and guanine) are the nucleobases used in the information carrying machinery of the DNA and RNA. Simple heterocyclic molecules could be aimed in millimetric observations of dense clouds in interstellar and circumstellar environments. Simple heterocyclic compounds, similarly to the PAHs are expected to be abundant, because both kinds of molecules are resistant to UV radiation (Peeters et al., 2005). Some of these species that could be targets for millimetric observations are: oxazole (C_3H_3NO), furan (C_4H_4O), pyrrole (C_4H_4NH), pyridine (C_5N_5N). Oxazole (Figure 2-6) is of particular interest,

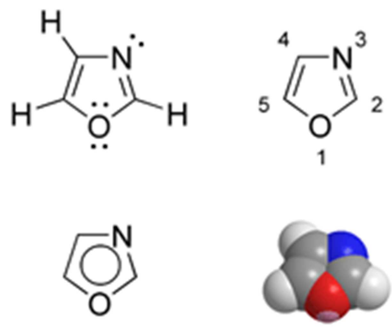

Figure 2-6.   Oxazole

because, besides being a relatively small molecule (8-atoms), one of its derivatives, amino-oxazole, has been proposed as the precursor of pymidine ribonucleotides, in the scenario of the "RNA world" for the origin of life on Earth (Powner et al., 2009).

3) The spiral structure of the Galaxy

Our Galaxy should not be very different from other spiral galaxies (Figure 2-7). Its main components are a flat rotating disk of stars and gas, an almost spheroidal bulge of yellow color containing mainly old stars at the center, and a bar-shaped distribution of gas and stars. Everything is contained in an extended, low density halo. In the disk the gas and dust, which are always mixed, are strongly concentrated in a thin layer of about 100 pc thickness. The Sun is at 8 kpc from the Galactic center, half-way between the center and the outskirts of the Galaxy. The very young and luminous stars and the molecular clouds are concentrated along spiral arms, and for this reason we call these objects "tracers" of the spiral structure. In the present context we will only discuss the spiral structure, i.e., we are interested in the position and shape of the arms, their stellar and gaseous content, their role as a cause of star formation, the velocity of the spiral pattern, the presence of resonances, the lifetime of the arms, the magnetic field in the arms, and the exact meaning of what is a "density wave".

Figure 2-7. *The barred spiral galaxy M95, not very different from the Milky Way*.

We have an idea of the general aspect of the spiral structure based on the images of other nearby spiral galaxies. Many of them are seen face-on, like M95 (above). In our Galaxy, however, we are in a position from where it is very difficult to see the structure. The Sun is close to the middle plane of the disk, and the same happens to the spiral arms, so that the arms are seen superimposed, and the lines of sight to the arms cross long distances in regions with maximum gas density, producing a high visual extinction. Only within about 3 kpc from the Sun one can use visual tracers to study the arms. The general spiral structure has to be studied by means of radio (including mm/sub-mm) and far infrared tracers, since the insterstellar medium is transparent at those wavelengths. This is illustrated in the Figure 2-8 taken from Lépine et al. (2011a), where the green points represent the Open Clusters and the orange ones the Cepheid stars, which are both optical tracers, only seen in the solar neighborhood. The blue points represent the position of CS molecular sources, which were detected at radio frequencies (Bronfman, Nyman & May 1996).

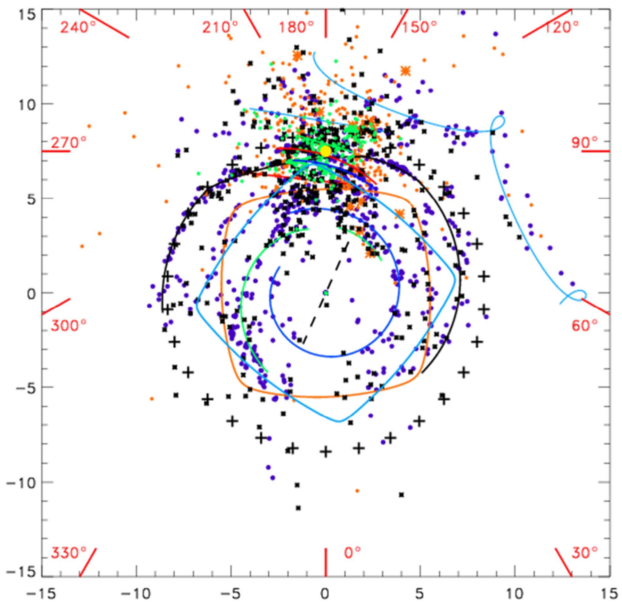

Figure 2-8. *The spiral structure of the Galaxy traced by CS sources (blue points), Open Clusters (green points) and Cepheids (orange color points). The position of the Sun is indicated by a yellow dot. The scales on the two axes are in kpc, and the red scale indicate the galactic longitudes. The crosses indicate the corotation radius*

It can be seen from this figure that the Galactic structure is very badly defined on the lower part of the figure, which corresponds to the opposite side of the Galaxy with respect to the center. Some attempts have been made to fit either resonant orbits (like in the figure) or logarithmic spirals (Russeil, 2003, Paladini, 2004) but none are convincing, since there are many points in regions between the fitted lines.

The results of a new CO survey were published very recently by Dame and Thaddeus (2011), who have identified a molecular arm in the far outer Galaxy, at the longitude range from 13^{o} to 55^{o}. This survey still leaves the symmetrical region between about 310^{o} and 350^{o}, which must be observed from the Southern Hemisphere, to be explored. Similarly, a nice map of molecular clouds in the disk was published by Hou et al (2009), but it is incomplete in the same longitude range (310^{o} to 350^{o}).

3.1.Why should we investigate the spiral structure?

Obtaining a much better and complete description of the structure is a way of testing the complex physics of the spiral arms and understanding the star formation process, and consequently, the evolution of galaxies. There are several advantages in observing our Galaxy compared to other ones. In our Galaxy, we are in a good position to observe the components of velocities of interstellar clouds which are the most important ones to understand the spiral arms: the components that are parallel the plane. In addition, due to relatively short distances, we are able to see the details of the interaction of the molecular clouds with the potential wells which correspond to the arms.

There are still controversies concerning the basic nature of the arms. Roberts (1969) first suggested that a shock front occurs as the gas of the disk flows through a spiral-shaped potential minimum, and that the shock triggers the star formation process. Another theory is the "sequential self-propagating star formations". According to this idea, massive stars at the end of their life produce strong stellar winds and/or supernova explosions, which can compress the neighboring molecular clouds and trigger their gravitational collapse, producing new generation of stars. This process would continue with the new generation of stars, and could propagate over large distances. However, Sartori, Lépine & Dias (2003) showed that in sequence of stellar associations in Sco, Cen, Lup and Crux, which were considered as the best nearby example of sequential star formation, the ages of the associations, did not fit the model. It has not been proved, for instance, that supernova shocks are efficient in triggering star formation, instead, they are often believed to interrupt it.

A third model to explain the spiral arms was introduced by Kalnajs (1973) in a first simplified version. In this model, the stellar orbits are closed, with an elliptical aspect, when they are seen in a frame of reference that rotates with a constant velocity Ω_p, which is the rotation speed of the spiral pattern. At least for a part of the stars, the orbits show a certain organization, presenting a small systematic change in the orientation of the orbits of successive sizes, so that the orbits come close together in some regions of the disk. The regions where the orbits are close together have a larger stellar density than the average density in the disk, and therefore, they can be seen as regions of lower gravitational potential, like potential "grooves" in the disk. The orbits are not always elliptical; they can get square-like aspect where the epicycle frequency is 4 times the frequency rotation around the galactic center (the 4:1 resonance, see Figure 2-9 below). This model predicts the existence of spiral arms that do not have the logarithmic spiral shape, but can have "polygonal" shapes, with a succession of almost straight segments, as observed in many galaxies (Chernin, 1999). Lépine et al. (2011a) claim to have identified arms with shapes that can be explained by resonant orbits, precisely where they are expected from theory. The particularity of this interpretation of the nature of the arms is that their shape is purely governed by stellar orbits, and not by the gas or by shock waves. This model even predicts the existence of parts of arms with reverse curvature (concave, if seen from a point very distant from the center). For this reason it is important to obtain the precise form of the arms, and be able to find the places where there are changes in direction, in order to identify the resonant orbits, instead of simply attempting to fit logarithmic spirals.

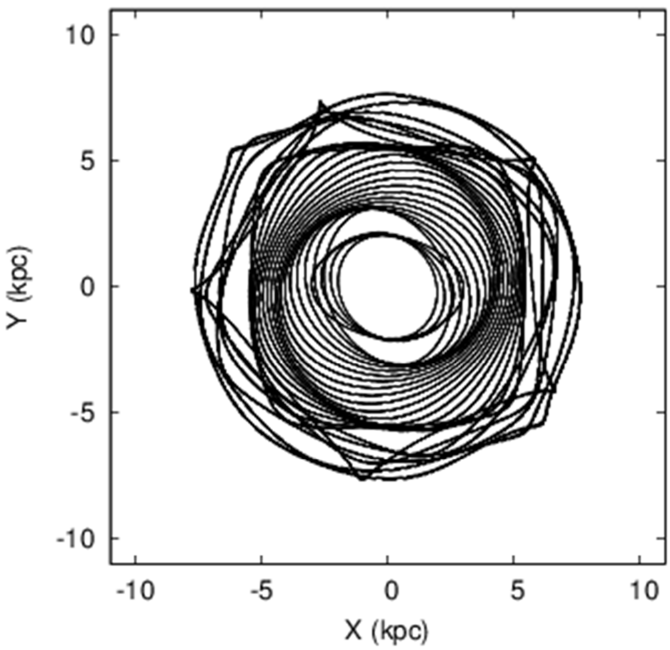

Figure 2-9. *A series of closed stellar orbits computed for the potential of our Galaxy, by T. Junqueira (PhD student at IAG-USP)*

This model is rich in consequences. The potential of the Galaxy, instead of having a sine function behavior in azimuth, as it was described since the first models of spirals by Lin and Shu (1964), is seen as composed of narrow channels or grooves situated where the stellar orbits come close together, superimposed on the axis-symmetric potential. Hydrodynamic simulations performed by the same group show that the gas of the disk, as it crosses the spiral arms, is trapped in the elongated potential wells, and it tends to flow along them. The gas flow along such arms is a good explanation for what radio-astronomers used to call in the past the "3 kpc expanding arm", as arms made of stellar orbits do not expand. A major consequence of this gas flow is a "pumping out" effect at the corotation resonance (where the material of the disk and the spiral pattern rotate with the same velocity, $\omega = \omega_p$). This resonance is situated at 1 kpc beyond the solar orbit, and at that radius there is a ring-shaped void of gas, like a Cassini gap in the disk, which was shown to really exist through an analysis of neutral hydrogen (21 cm) surveys (Amôres et al., 2009). This gap has a strong influence on the metallicity distribution in the Galaxy, as it acts like a barrier between the two sides of the corotation (Lépine et al, 2011b). Many of the predictions made by the new interpretation of spiral arms should be observable by mapping the velocity gradients of the gas in selected directions.

Another test of spiral arm models is the vertical structure (in the *z* direction, perpendicular to the plane), a question that has almost not been explored. A theoretical model by Mishurov (2007) shows what is expected from the classical theory of arms; elongated structures reaching about 0.2 kpc from the plane are predicted. Such structures could in principle be observed by CO line mapping of regions where the arms are seen tangentially.

3.2. Star formation, molecular clouds and spiral structure

A point of major interest related to the spiral arm structure is the star formation mechanism. In reality, these two studies cannot be separated one from the other. Massive star formation occurs only in the arms and the young stars and HII regions that they produce are tracers of the spiral structure; the initial velocities of the stars inform us on the gas velocity from which they were formed.

Observations of young stellar objects (YSO's) and newly-born, low and intermediate-mass stars in dark clouds have shown that typically, over 50% of their luminosity is emitted beyond λ=20 μm (Wilking et al. 1985), and the bulk of this radiation comes from dust heated by these newly-born "invisible" stars.

What are the mechanisms which control the star formation rate (SFR)? On a large scale, almost all chemical evolution models consider that this rate depends only on the surface density of gas μ_g, and use an expression like SFR $\propto \mu_g^{\alpha}$, known as the Schmidt´s law, where α is a power, usually taken equal to 1.4, following Kennicutt (1998). This concept totally ignores the presence of spiral arms. It would seem reasonable to suppose that, since the spiral arms are the star-formation machines of the Galaxy, the SFR depends on the rate at which the gas of the disk is fed into the arms. That is, the SFR should be proportional to the gas density and to the relative velocity $|\Omega - \Omega_p|$. Such a law could be verified by measuring an SFR indicator, like for instance the density of HII regions, at different galactic radii.

At smaller scales, other factors could interfere, like the turbulence within the clouds. Broad line widths ranging from a few to more than 10 times the sound speed and interstellar magnetic field strengths of a few microgauss are measured which indicate that the turbulent motions are supersonic and trans-Alfvenic (Elmegreen & Scalo, 2004; Heiles & Troland, 2005). It is not clear what keeps the turbulence for long times in clouds, since in theory, the turbulence should dissipate quite rapidly. Magneto-hydrodynamic (MHD) simulations (Melioli et al., 2006, Leão et al., 2009) suggest that SNs could be a main source of turbulence due to the large amount of energy they inject into the clouds. Other hydrodynamic simulations of the gas of the disk penetrating a groove-like spiral arm (Falcetta-Gonçales et al. 2011) show that this process, which is permanently on-going, is a strong source of turbulence. This is a new mechanism, which has not yet been fully explored. Many authors believe that turbulence is essential to enhance the SFR, as it produces local peaks of density which could then meet the Jeans criterion for gravitational collapse.

Another factor which probably controls the star-formation rate in a dense cloud is the magnetic field, since the magnetic pressure and tension resists to the collapse of the clouds. If the magnetic field were perfectly frozen into the gas during the gravitational collapse, the magnetic field strength of a typical star like our Sun would be more than 10 orders of magnitude larger than we observe today. Thus, there must be some mechanism that removes the excess of magnetic field during the star formation process. Santos-Lima et al. (2010) have recently proposed and tested with MHD numerical simulations a mechanism that is able to remove the excess of magnetic flux from a collapsing cloud, by the action of the turbulence itself. Magnetic reconnection of the field lines in the turbulent fluid is able to transport the magnetic field diffusively from the inner denser regions to the outskirts of the collapsing cloud. Later in this star formation process, the same mechanism is also able to remove the magnetic field excess from the protostellar disk that forms around the newborn star (Santos-Lima et al., 2011).

It would be of interest to measure both the intensity and the direction of the magnetic field in the spiral arms and within the molecular cloud cores to probe the magnetic flux transport mechanism above. The intensity of the magnetic field can be measured in molecular clouds using the Zeeman effect in CN molecule at 3 mm (see results obtained by Crutcher et al., 1999). The orientation of the field can be studied by means of the polarization of the sub-mm radiation; sub-mm studies directly see the thermal emission from the dust grains. The detection of polarization (like for instance in Orion KL, by Hildebrand et al., 1984) at sub-mm wavelengths implies that the dust grains are elongated and aligned.

However, up to now, most investigations have been based on optical studies of polarization. For instance, in a study of a specific cloud , Vrba et al. (1981) found that the magnetic field increases strongly from the inter-cloud medium to the inner cloud cores. In the density range $50 < n < 10^3$ cm, the magnetic field was found to increases as $B \sim n^{0.38}$. Magnetic fields smaller than 1 mG have been found in dark clouds, but polarization measurements at sub-mm wavelengths could possibly reveal stronger B values in dense cores. In principle, a field of 1 mG would prevent the formation of low-mass stars, because the critical mass M_c for fragmentation depends on B and the cloud density like $M_c \sim B^3 n^{-2}$ (Mouschovias 1978). Therefore, a detailed mapping of the polarization – and consequently of the magnetic field – is fundamental to understand the physical processes that act in star-forming regions.

The polarization studies at sub-mm wavelengths will benefit from the systematic polarization mapping of the Galaxy that will be made at optical wavelengths by the robotic 80 cm telescope South Pol supported by FAPESP, which will perform a Survey of the Polarized Southern Sky (PIs A.M. Magalhães and C. Mendes de Oliveira).

Going back to the spiral structure, different Brazilian groups have been working on detailed investigation of distant HII regions of the disk, associated with clusters of massive stars and molecular clouds (eg. Roman-Lopes and Abraham, 2006, Moisés et al., 2011). By means of infrared color-magnitude diagrams, these authors have derived the distances of the objects, which are not observable in the visible. One group reports serious discrepancies with distances derived from the kinematic method, which are sometimes found to be up to 2 kpc larger than those measured by other means (see for instance the photometric distances of groups of OB stars measured by Blum et al. (2000), and Figueredo et al. (2008). This emphasizes the difficulties of the kinematic method of determining distances. Apart from the problem of distance ambiguity (between the two solutions given by the method for the sources situated within the solar circle), the method is not precise. It is based on the hypothesis of circular rotation of the gas and stars around the Galactic center, while there are clear departures from circularity. In order to obtain precise distances of the spiral arms, it will be useful to make use of a number of objects with well determined distances, to calibrate the kinematic distances.

A possible class of distance calibrators are the Cepheids, by means of the period-luminosity relation. The presently on-going VISTA deep infrared survey (http://mwm.astro.puc.cl/mw), with repeated observations of the same regions to detect variability of stars, will certainly lead to the discovery of many distant Cepheids in the longitude range of interest for our studies. Another distance calibrator is provided by the VLBI measurements of the trigonometric parallax of masers associated with star forming regions. This method is the one used by the VERA project in Japan. For instance Nagayama et al. (2011) obtained the distance of a galactic star formation situated at 5 kpc with an error bar of 0.2 kpc. We expect to be able in future to constitute a Latin-American equivalent of VERA for the Southern Hemisphere, starting from the LLAMA seed.

We return now to the strategy for determining the exact geometry of the arms and discovering the distant arms. The tracers can be HII regions or molecular clouds; in particular, the compact HII regions are of special interest since they reveal the position of early stages of star formation. They can be detected from their free-free emission, and then their velocity determined by means of radio-recombination lines, which are intense at mm wavelengths, presenting maser effect. A first step could be a survey of a narrow band of the galactic plane with a wide-band submm bolometer camera similar to LABOCA one of the APEX radiotelescope, to locate the distant HII regions. Such a camera covers a larger area of the sky in a single observation, and will produce a catalog of candidate sources in a shorter time than a single beam observation. These observations will be followed by recombination line observations which will confirm the nature of the sources and measure their radial velocity. However, the velocities do not guarantee a good enough distance determination, as it was discussed above. It will be necessary to identify a few good distance calibrators in each arm to place them at their correct position.

4) Other scientific uses of LLAMA

During the workshop LLAMA which was held at FAPESP on August 8 and 9 many other possibilities of scientific use of LLAMA were discussed. These include the observation of exoplanets, galaxies at redshift z~1, the study of SNRs interacting with molecular clouds, the Sunyaev-Zeldovich effect, the comparison of the optical and radio reference frames for astrometry, solar physics, etc. The presentations are available at the site http://www.fapesp.br/6472

In addition to the scientific cases discussed during that meeting, other possibilities exist, like for instance observations of **hyper-starbursts** that took place less than 1 gigayear (z > 6.0) after the Big Bang. Recent observational evidences are discussed by Walter et al. (2009); theoretical computations are presented by Dekel et al. (2009).

References

Amores, E.B., Lépine, J.R.D., Mishurov, Yu.N., 2009, MNRAS, 400, 1768

Andrade D. P. P. , Rocco, M. L. M., Boechat-Roberty, H. M., 2010, MNRAS 409, 1289

Blandford, R. D., Payne, D. G., 1982, MNRAS 199, 883

Blum, R. D., Conti, P. S., Damineli, A. , 2000, AJ, 119, 1860

Bronfman, L., Nyman, L.-A., May, J., 1996, A&A Suppl. Ser 115, 81

Cami, J., Bernard-Salas, J., Peeters, E., Malek, S.E., 2010, *Science* 329, 1180

Caproni, A., Livio, M., Abraham, Z., Mosquera Cuesta, H. J., 2006, ApJ 653, 112

Chernin, A.D.,1999, MNRAS 308, 321

Crutcher, R.M., Troland, T.H., Lazareff, B., Paupert, G., Kazès, I., 1999, ApJ 514, L121

De Barros, A.L.F., Bordalo, V., Seperuelo Duarte, E., da Silveira, E. F., Domaracka, A., Rothard, H., Boduch, P., 2011, A&A 531, 160

de Gouveia Dal Pino, E. M., Piovezan, P. P., Kadowaki, L. H. S., 2010, A&A 518, 5

Dekel, A., Birnboim, Y., Engel, G., Freundlich, J. et al., 2009, Nature 457, 451

Broderick, A.E., Fish, V. L., Doeleman, S.S.; Loeb, A. ,2011, ApJ, 738, 38

Dame, T. M., Thaddeus, P., 2011, ApJ, 734, 24

Doeleman, S.S., Weinroub, J., Rogers, A., Plambeck,R., Freund, R., et al. 2008, Nature 455, 78

Doeleman, S.S., Fish, V.L., Broderick, A.E., Loeb, A., Rogers, A.E.E., 2009, ApJ 695, 59

Doeleman,S.S., Shen, Z. –Q., Rogers, A. E. E., Bower, G. C., Wright, M. C. H., et al. 2001, AJ 121, 2610

Doelman, S.S., Agol, E., Backer, D., Baganoff, F.,Bower, G. C., 2011, arxiv.org/abs/0906.3899

Elbaz, E., Le Floc'h, E., Dole, H., Marcillac, D., 2005, A&A, 434, L1

Elmegreen, B. G., Scalo, J., 2004, ARA&A, 42, 211

Falcetta-Gonçales, D., et al., 2011, in preparation

Falcke, H., Melia, F., Agol, E., 2000, ApJ 528, 13

Figuerêdo, E. Blum, R. D., Damineli, A., Conti, P. S., Barbosa, C. L., 2008, AJ, 136, 221

Fossati, G., Maraschi, L., Celotti, A., Comastri, A., Ghisellini, G., 1998, MNRAS 299, 433

Greenhill, L.J., Kondratko, P.T., Moran, J.M., Tilak, A., 2009, ApJ 707, 787

Heiles, C., Troland, T. H., 2005, ApJ, 624, 773

Hildebrand, R. H., Dragovan, M., Novak, G., 1984, ApJ 284, L51

Hollis, J. M., Jewell, P. R., Lovas, F. J., Remijan, A. 2004a, ApJ 613, 45

Hollis, J. M., Jewell, P. R. Lovas, F. J., Remijan, A., Møllendal, H., 2004b, ApJ 610, 21

Hollis, J. M., Lovas, F. J., Remijan, A. J., Jewell, P. R., Ilyushin, V. V., Kleiner, I., 2006a, ApJ 643, 25

Hollis, J. M.; Remijan, Anthony J.; Jewell, P. R.; Lovas, F. J. 2006b , ApJ...642..933H

Hou, L. G., Han, J. L., Shi, W. B., 2009, A&A, 499, 473

Kalnajs, A.J., 1973, Proc. ASA 2(4), 174

Kennicutt, R.C., 1998, ApJ, 498, 541

Kuo, H-L., Remijan, A. J., Snyder, L. E., Looney, L. W., Friedel, D. N., Lovas, F. J., McCall, B. J., Hollis, J.M., 2010, International Symposium On Molecular Spectroscopy (Ohio State University) .

Leão, M. R. M., de Gouveia Dal Pino, E. M., Falceta-Gonçalves, D., Melioli, C.;, Geraissate, F. G.M., 2009, MNRAS, 394, 157

Lépine, J. R. D., Roman-Lopes, A., Abraham, Z., Junqueira, T. C., Mishurov, Yu. N., 2011a, MNRAS 414, 1607

Lépine, J. R. D., Cruz, P., Scarano, S. Jr., Barros, D. A., Dias, W. S., Pompéia, L., Andrievsky, S. M., Carraro, G., Famaey, B., 2011b, MNRAS.tmp.1339L

Lin, C. C., Shu, Frank H., 1964, ApJ, 140, 646

Lovas, F. J., Hollis, J. M., Remijan, A.J., Jewell, P. R., 2006, ApJ, 645, 137

Melioli, C., de Gouveia Dal Pino, E. M., de La Reza, R., Raga, A., 2006, MNRAS, 373, 811

Mishurov, Y. N., 2007, ARep, 51, 215

Miyoshi, M., Furuya, R. S., Kawaguchi, N., Nakajima, J., Irimajiri, Y. et al., 2011, Astron. Soc. Pacific Conf. Series, 439, 279. • Mishurov, Yu.N., 2007, Astronomy Reports 51, No. 3, 215

Moisés, A.,P., Damineli, A., Figurêdo, E., Blum, R. D., Conti, P. S., Barbosa, C. L., 2011, MNRAS, 411, 705

Mouschovias, T. Ch., 1978, in Protostars and Planets, ed. T. Gehrels (Tucson, University of Arizona Press)

Nagayama, T., Omodaka, T., Nakagawa, A., Handa, T., Homma, M., et al, 2011, PASJ, 63, 23

Paladini, R., 2004, MNRAS, 347, 237

Peeters, Z., Botta, O., Charnley, S. B., Kisiel, Z., Kuan, Y.-J., Ehrenfreund, P., 2005, A&A, 433, 583

Pilling, S., Andrade, D. P. P., Do Nascimento, E. M., Marinho, R. R. T., Boechat Roberty, H. M, et al. , 2011, MNRAS, 411, 2214

Planck collaboration, Abergel, A. et al.,2011, astro-ph > arXiv:1101.2032

Powner, M.W., Gerland, B., Sutherland, J.D., 2009, Nature, 459, 239

Riechers, D.A., Dominik, A., Pope, A., Armus, L., Daddi, E., 2010, AAS, 215, 410.21

Roberts, W. W., 1969, ApJ, 158, 123

Roman-Lopes, A. , and Z.., Abraham, 2006, AJ 131, 951

Russeil, D., 2003, A&A, 397, 133

Santos-Lima, R., Lazarian, A., de Gouveia dal Pino, E. M., 2010, ApJ , 714, 442

Santos-Lima, R., de Gouveia Dal Pino, E. M., Lazarian, A., 2011, ApJ, in press.

Sartori, M. J., Lépine, J. R. D., Dias, W. S., 2003, A&A, 404, 913

Target et al. 2011, arquiv1107.2397v1

Tercero, B., Cernicharo, J., Pardo, J. R., Goicoechea J. R., 2010, A&A, 517, A96

Vrba, F.J., Coyne, G.V. & Tapia, S., 1981, ApJ, 243, 489

Walter, F., Riechers, D., Cox, P., Neri, R., Carilli, C. et al., 2009, Nature, 457, 699

Wilking, B.A., Harvey, P.M., Joy, M., Hyland, A.R. & Jones, T.J., 1985, ApJ, 293, 165

Yusef-Zadeh, F., Wardle, M., Heinke, C., Dowell, C. D., Roberts, D., et al. 2008, ApJ, 682, 361

Zack, L. N.; Halfen, D. T.; Ziurys, L. M. 2011, ApJ 733, 36