PRE-MAIN SEQUENCE VARIABLES IN THE VMR-D: IDENTIFICATION OF T TAURI-LIKE ACCRETING PROTOSTARS THROUGH SPITZER–IRAC VARIABILITY

T. Giannini1, D. Lorenzetti1, D. Elia2,3, F. Strafella3, M. De Luca1,4, G. Fazio5, M. Marengo5, B. Nisini1, and H. A. Smith5

1 INAF—Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monte Porzio, Italy; giannini@oa-roma.inaf.it, dloren@oa-roma.inaf.it, nisini@oa-roma.inaf.it, deluca@oa-roma.inaf.it
2 Universidade de Lisboa, Faculdade de Ciencias, Centro de Astronomia e Astrofisica da Universidade de Lisboa, Observatorio Astronomico de Lisboa, Tapada da Ajuda1349-018, Lisboa, Portugal; eliad@ual.pt
3 Dipartimento di Fisica, Univ. del Salento, CP 193, I-73100 Lecce, Italy; eliad@le.infn.it, francesco.strafella@le.infn.it
4 LERMA-LRA, UMR 8112, CNRS, Observatoire de Paris and Ecole Normale Superieure, 24 Rue Lhomond, 75231 Paris, France; massimo.de.luca@lra.ens.fr
5 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA; mmarengo@cfa.harvard.edu, hsmith@cfa.harvard.edu

Received 2009 April 24; accepted 2009 June 29; published 2009 September 24

ABSTRACT

We present a study of the infrared variability of young stellar objects by means of two Spitzer–IRAC images of the Vela Molecular Cloud D (VMR-D) obtained in observations separated in time by about six months. By using the same space-born IR instrumentation, this study eliminates all the unwanted effects due to differences in sensitivity, confusion, saturation, calibration, and filter bandpasses, issues that are usually unavoidable when comparing catalogs obtained from different instruments. The VMR-D map covers about 1.5 deg2 of a site where star formation is actively ongoing. We are interested in accreting pre-main sequence variables whose luminosity variations are due to intermittent events of disk accretion (i.e., active T Tauri stars and EXor-type objects). The variable objects have been selected from a catalog of more than 170,000 sources detected at an S/N ≥ 5. We then searched the sample of variables for ones whose photometric properties such as IR excess, color–magnitude relationships, and spectral energy distribution, are as close as possible to those of known EXor’s. Indeed, the latter are monitored in a more systematic way than T Tauri stars and the mechanisms that regulate the observed phenomenology are exactly the same. Hence, the modalities of the EXor behavior are adopted as driving criterion for selecting variables in general. We ultimately selected 19 bona fide candidates that constitute a well defined sample of new variable targets for further investigation (monitoring, spectroscopy). Out of these, 10 sources present a Spitzer MIPS 24 μm counterpart, and have been classified as three Class I, five flat spectrum, and two Class II objects, while the spectral energy distribution of the other nine sources is compatible with evolutionary phases older than Class I. This is consistent with what is known about the small sample of known EXor’s, whose properties have driven the present selection and suggests that the accretion flaring or EXor stage might come as a Class I/Class II transition. We also present new prescriptions that can be useful in future searches for accretion variables in large IR databases.

Key words: catalogs – infrared: ISM – infrared: stars – stars: formation – stars: pre-main sequence – stars: variables: other

Online-only material: color figures

1. INTRODUCTION

Young stellar objects (YSOs) from low to intermediate mass objects (0.5–8 M⊙) accumulate the majority of their final mass during the so-called main accretion phase lasting about 105 years. After this period, they continue to accrete, although at lower rates. According to a commonly accepted view, material that falls onto the circumstellar disk crosses the viscous part of the disk itself and finally jumps onto the stellar surface through the magnetic interaction lines (Shu et al. 1994). These accretion phenomena are observationally signaled by intermittent outbursts (usually detected in the optical and/or in the near-IR bands) due to the sudden increase of the mass accretion rate by orders of magnitude (Hartmann & Kenyon 1985). These events are quite common during the pre-main sequence life (T Tauri and Herbig Ae/Be stars) and, when some recurrent flaring events are recognizable in their light curves, they are called FUor or EXor outbursts depending on their intensity and duration (Herbig 1989; Hartmann & Kenyon 1996). FUor’s are rarer, and experience particularly intense outbursts (5–6 mag) followed by long periods (tens of years) during which the object remains bright. Conversely, typical EXor variability (Herbig 2007, 2008; Lorenzetti et al. 2006, 2007, 2009, hereinafter L07, L09) and the variability of accreting T Tauri stars is characterized by less intense (3–4 mag) and more short-lived outbursts (from months to a year) superposed on longer periods (few years) of quiescence. Historically, all the known accreting T Tauri stars, FUor’s, and EXor’s were first identified in the visual bands; as a consequence, being quite unextincted, they have been usually associated with the last phases of pre-main sequence evolution. However, there is no physical reason that prevents the associated phenomena from occurring as well during more embedded, and consequently earlier, phases. In fact, an increasing number of similar objects has been identified and studied (e.g., Hodapp et al. 1996, 1999; Reipurth & Aspin 2004; Kospál et al. 2007; Sicilia-Aguilar et al. 2008). Obviously there are many kinds of variable objects besides accretion and eruptive variables: cataclysmic, pulsating (Mira), and eclipsing variables, for example. Hence, although accreting ones are expected to prevail in star formation regions, great care has to be taken evaluating possible contamination effects.

So far, the low-mass disk accretion variables are extensively studied only in nearby star-forming regions (at distances less than 300 pc), but now Spitzer sensitivity has enlarged the

606
accessible volume, thus allowing to investigate that population at larger distances, as well. Such a chance is relevant for investigating the interplay between low-, intermediate-, and even high-mass star formation processes occurring in the same region.

We recently used the InfraRed Array Camera (IRAC, Fazio et al. 2004) and the Multi-band Imaging Photometer for Spitzer (MIPS, Rieke et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004) to survey $1.5 \text{deg}^2$ of the Vela Molecular Cloud-D (VMR-D; Giannini et al. 2007), a star-forming region in the southern sky on which we have accumulated a large variety of photometric (Massi et al. 1999, 2000, 2003; De Luca et al. 2007) and spectroscopic (Giannini et al. 2005; Lorenzetti et al. 2002) data, along with detailed maps of the gas (Elia et al. 2007) and dust (Massi et al. 2007) emission. The total integration time requested for the IRAC map was obtained by co-adding two individual maps, each integrating for half of the total time and separated by about one semester in time. This observational mode additionally provided us with two separate sets of data ideally suited for investigating the mid-infrared variability (over six months) of our sample of young objects. While this multiple epochs technique has been commonly used to acquire Spitzer/IRAC maps of star-forming regions, to allow easy removal of transients and artifacts, these data sets have been seldom analyzed to study the variability of the sources. Given the features that characterize accreting T Tauri stars, EXor’s, and FUor’s, the relatively short period between the two IRAC data sets does not seem suitable for a systematic search for FUor’s, that usually remain stable for decades. Hence, in the following discussion, when speaking of accreting variables, we will refer to the class of active T Tauri stars or even to EXor’s, given their similarities in the accretion modalities.

The advantages of our approach are many: (1) the time elapsed between the two maps (six months) is well suited for sampling the most common accretion events; (2) because IRAC wavelengths are less affected by extinction than optical ones, IRAC allows us to enlarge the effective volume under investigation compared to optical observations, while preserving the needed sensitivity; (3) the IRAC bands (3.6, 4.5, 5.8, and 8.0 $\mu$m) cover the spectral range where disks emit the largest part of their energy, and (4) a comparison between two sets of data obtained with the same instrumentation removes the confusion introduced by instrumental differences of sensitivity, beam confusion, saturation levels, calibration, and/or filter bandpasses.

Our primary goal is to select valid candidates of variable accreting objects in VMR-D, a star-forming region in which such a search has never been done before. Once completed, we expect that photometric and spectroscopic monitoring will be in order to confirm and analyze their nature. Secondly, we want to use our sample to provide useful distinguishing prescriptions for finding similar sources in other star-forming regions, and thus to increase the number of known objects in a systematic way. In this respect, we remind that our analysis cannot account for the complete population of YSOs in accretion, since they spend the major part of their lifetime in quiescence or in a steady state. A thorough analysis in that sense, designed to select YSOs within the large Spitzer sample of midplane objects by reducing contamination from spurious sources, has been recently presented by Robitaille et al. (2008).

This paper follows the following structure: after having presented our observations (Section 2) and defined the variable objects (Section 3), we discuss our results (Section 4) with emphasis on the source evolutionary stage and location inside the cloud. Finally, we present our conclusions (Section 5).

2. OBSERVATIONS

In this paper, we make use of a map of approximately 1.5 $\text{deg}^2$ of the VMC-D that we obtained with Spitzer-IRAC Cycle-3 GTO (PID: 30335; PI: G.Fazio) at 3.6, 4.5, 5.8, and 8.0 $\mu$m. The area chosen for mapping is the same we have investigated at other wavelengths (see Section 1). Observations were carried out in two separate AORs on 2007 February 21 UT and 2007 July 4 UT (AOR Keys: 17606656 and 17606912, respectively) by adopting half-array cross scan offsets. The cross scans also enabled us to obtain much more reliable point source photometry in crowded regions.

A set of 256 frames, each 10.4 s integrated, was used, resulting in a total integration time of 20.8 s per pointing. In regions, where bright sources were expected we obtained a few frames in High Dynamical Range (HDR) mode to obtain unsaturated fluxes. The IRAC data were reduced using the IRAcproc package (Schuster et al. 2006), to obtain a single flux calibrated mosaic combining all the individual exposures in each epoch (separately), on a pixel grid of $0.′′8627$/pixel. IRAcproc is based on the Spitzer Science Center mosaic software MOPEX and provides enhanced outlier (cosmic rays) rejection. The IRAC point-source photometry was done using DAOPHOT package (Stetson 1987). Image mosaicing and all the details relative to both the point-source function (PSF) photometry extraction and the construction of a catalog containing more than 170,000 IRAC sources are presented in a dedicated paper (F. Strafella et al. 2009, in preparation). Here we note that the spatial resolution of Spitzer in the IRAC bands is of the order of $2′′$. Because of the different satellite orientations in the two epochs, the maps do not coincide precisely, as shown in Figures 1 and 2; moreover, band 1 (3.6 $\mu$m) is acquired simultaneously with band 3 (5.8 $\mu$m), while band 2 (4.5 $\mu$m) simultaneously with band 4 (8.0 $\mu$m); also these couples of maps are not exactly coincident although to a much lesser extent. As a result, in the following we will refer only to those sources detected in the common portion (between both different epochs and different bands), in order to have, for any considered source and for any considered band, two observations available for comparison.

3. IDENTIFICATION OF VARIABLE OBJECTS

Since we are interested in selecting variable YSOs, the two independent subcatalogs were searched using the following procedures. Firstly, the variable objects within a given band were defined with these selection criteria:

1. detection in the considered band at an $S/N$ level $\geq 5$ in both epochs, separately,
2. ratio between the flux variation and its error, $(F1−F2)/\sigma(F1−F2) \geq 5$, and
3. object brighter than a given threshold in both periods; namely $\leq 16$ mag (band 1), $\leq 15.5$ mag (band 2), $\leq 13.5$ mag (band 3), and $\leq 12.5$ mag (band 4).

The first criterion picks up objects associated with real detections, minimizing any contamination by unwanted effects such as spikes and artifacts. The second one allows us to select genuine variations well above the photometric errors. The third one is dictated by the completeness limits of our subcatalogs (see F. Strafella et al., 2009, in preparation and Figure 3). Moreover, since our sample of selected variables will plausibly need near-IR spectroscopy to be definitely validated, from the start we
Figure 1. IRAC maps at 3.6 μm obtained in two different epochs. Due to the satellite orientation, they are rotated in a different way. The common part is clearly recognizable. The contours of our CO map (Elia et al. 2007) are superposed (in green). The 5.8 μm channel is acquired simultaneously, therefore it presents the same superposition. The location of the selected variables is shown with red dots.

(A color version of this figure is available in the online journal.)

Figure 2. As in Figure 1, but for the 4.5 μm channel (acquired simultaneously to the 8.0 μm one). Notice that the common part between the two epochs is slightly different from that of channels 3.6 and 5.8 μm. Here, for completeness, our dust continuum map at 1.2 mm (Massi et al. 2007) is superposed (in green).

(A color version of this figure is available in the online journal.)
symmetrical around zero. This effect is clearly a consequence of the magnitude variation.

13.5, and 12.5 mag in band 1, 2, 3, and 4, respectively).

The magnitude variation is given. Each of the four distributions shows two peaks around a variation of ~0.4–0.6 mag, roughly symmetrical around zero. This effect is clearly a consequence of our second selection criterion that validates only those variations significantly larger than their own errors.

We note that the gap in the distribution tends to be filled at the longer wavelength bands, because of both the increase of the level of the minimum around zero, and the progressive decrease in the height of the two peaks. This indicates that small percentage intensity variations occur preferentially at the longer wavelengths. A similar behavior has already been identified in the set of known eruptive young objects (although at different wavelengths, i.e., in the near-infrared bands); they are never observed to vary only in a single spectral band, and their percentage fluctuations usually decrease in amplitude with the wavelength (L07).

The above considerations lead us to pick up among the objects that passed our criteria, those simultaneously variable in both bands 1 and 2, remaining in this way with 53 sources. These have been examined one by one looking for their location in the original 3.6 μm mosaic and ruling out those sources located in the near proximity of very bright objects. In principle, PSF photometry should be less sensitive to contamination from nearby contributions, however artifacts associated to bright IRAC objects present different patterns in the two different epochs and this occurrence may mimic some spurious variability. As a result of such an inspection, six further sources have been dropped out, hence our final sample is constituted by a total of 47 objects, which represent the 0.22% of the detections (above the magnitude threshold) in both bands. These 47 variable objects will be considered in the following and a catalog of these sources is given in Table 2. Here, IRAC magnitudes (one line for each epoch) are given along with complementary (and not contemporary) photometry of the Two Micron All Sky Survey (2MASS; JHK) and MIPS (24 μm) counterparts (see below).

In order to verify whether or not the selected sources are intrinsically variable or perhaps appear as such because of some fluctuations of the local sky or background between the two epochs (for example inside the IR clusters, where the very localized diffuse emission may be relevant), we have plotted the variations (in band 1 and 2) of all the IRAC sources within 1′ from the selected variable. By doing so, we have temporarily relaxed our second criterion (otherwise no other variable could be found in the neighborhood). We did not find any source whose flux fluctuation was comparable with that of the selected

Table 1
Statistics of IRAC Variables

| Band | \( N_{ep}^a \) | \( N_{ep}^b \) | \( N_{var}^c \) | \( N_{dec}^d \) | \( N_{ris}^e \) |
|------|--------------|--------------|--------------|--------------|--------------|
| 3.6 μm | 138601 | 40382 | 306 | 190 | 116 |
| 4.5 μm | 126901 | 27519 | 201 | 108 | 93 |
| 5.8 μm | 24256 | 6751 | 121 | 65 | 56 |
| 8.0 μm | 12977 | 3207 | 84 | 45 | 39 |
| 3.6 and 4.5 μm | 114515 | 24482 | 53 | ... | ... |

Notes.

a Number of sources detected in the first epoch (this number does not change significantly in the second epoch).

b Number of sources whose magnitude is less than a given threshold (16, 15.5, 13.5, and 12.5 mag in band 1, 2, 3, and 4, respectively).

c Number of sources selected as variables (see text).

d Number of declining sources \((\text{mag}_{ep1} - \text{mag}_{ep2} < 0)\).

e Number of rising sources \((\text{mag}_{ep1} - \text{mag}_{ep2} > 0)\).
### Table 2
Magnitudes of the Selected Variables

| Ident. | α(2000) | δ(2000) | J | H | K | [3.6] | [4.5] | [5.8] | [8.0] | [24] |
|--------|---------|---------|---|---|---|-------|-------|-------|-------|------|
| 16186  | 45 29.7 | 50 48.1 | ··· | ··· | ··· | 13.50 | 12.96 | ··· | ··· | ··· |
| 17825  | 45 33.9 | 52 3.0  | ··· | ··· | ··· | 11.91 | 10.44 | 9.43  | ··· | 3.20 |
| 18018  | 45 34.4 | 50 3.8  | ··· | ··· | ··· | 13.12 | 12.49 | ··· | ··· | ··· |
| 18177  | 45 34.8 | 52 57.6 | 16.69 | 15.71 | 14.77 | 11.93 | 10.91 | 10.02 | 9.14  | ··· |
| 24218  | 45 49.8 | 56 56.5 | ··· | ··· | ··· | 14.96 | 14.46 | 14.15 | ··· | ··· |
| 24291  | 45 50.0 | 56 50.6 | ··· | ··· | ··· | 15.82 | 15.16 | 14.58 | ··· | ··· |
| 29062  | 46 01.5 | 41 20.2 | 16.37 | 15.43 | 15.60 | 14.95 | 15.02 | ··· | ··· | ··· |
| 34166  | 46 14.1 | 23 48.0 | ··· | ··· | ··· | 13.11 | 12.52 | 12.02 | 11.39 | ··· |
| 36255  | 46 19.2 | 51 9.4  | 11.52 | 11.22 | 11.13 | 11.46 | 11.49 | 11.48 | 11.49 | 11.49 |
| 39530  | 46 27.1 | 54 31.2 | ··· | ··· | ··· | 14.68 | 14.43 | 13.97 | 12.10 | ··· |
| 39917  | 46 28.1 | 54 31.9 | ··· | ··· | ··· | 15.20 | 15.09 | 14.05 | 13.03 | ··· |
| 44510  | 46 39.5 | 22 50.5 | ··· | ··· | ··· | 13.24 | 12.16 | 11.33 | 10.58 | 6.31 |
| 47193  | 46 46.2 | 50 24.5 | ··· | ··· | ··· | 14.46 | 14.47 | ··· | ··· | ··· |
| 47398  | 46 46.7 | 19 59.3 | ··· | ··· | ··· | 14.57 | 13.81 | 13.28 | 12.74 | ··· |
| 47407  | 46 46.7 | 52 52.4 | 16.68 | 15.08 | 14.30 | 13.41 | 13.00 | 12.49 | 11.60 | ··· |
| 48734  | 46 49.9 | 19 1.2  | 15.69 | 14.59 | 14.26 | 13.75 | 13.71 | 13.74 | 13.86 | ··· |
| 48885  | 46 50.3 | 52 57.0 | ··· | ··· | ··· | 13.10 | 13.03 | 12.82 | 12.83 | ··· |
| 50748  | 46 54.7 | 52 36.3 | 17.37 | 16.50 | 14.97 | 12.04 | 10.68 | 9.45  | 8.42  | 4.16 |
| 57549  | 47 9.8  | 56 31.7 | ··· | ··· | ··· | 13.06 | 12.64 | 12.17 | 11.36 | 9.88 |
| 62402  | 47 19.8 | 21 20.4 | ··· | ··· | ··· | 14.79 | 14.54 | ··· | ··· | ··· |
| 67878  | 47 30.6 | 28 22.4 | ··· | ··· | ··· | 15.47 | 15.46 | ··· | ··· | ··· |
| 68183  | 47 31.3 | 55 3.1  | 15.37 | 14.76 | 14.61 | 14.96 | 14.90 | ··· | ··· | ··· |
| 84520  | 48 0.4  | 20 37.2 | ··· | ··· | ··· | 13.36 | 12.59 | 11.91 | 11.22 | 7.70 |
| 85679  | 48 2.3  | 18 50.5 | 14.34 | 13.42 | 12.73 | 11.77 | 11.33 | 10.80 | 10.09 | 7.66 |
| 90096  | 48 10.0 | 19 57.9 | ··· | ··· | ··· | 13.93 | 12.17 | 11.77 | 11.33 | ··· |
| 95158  | 48 12.6 | 59 17.4 | 16.05 | 15.15 | 14.69 | 14.26 | 14.25 | 14.01 | ··· | ··· |
| 107546 | 48 42.8 | 17 32.1 | ··· | ··· | ··· | 13.90 | 13.83 | 13.83 | ··· | ··· |
| 109118 | 48 46.0 | 37 27.0 | ··· | ··· | ··· | 15.87 | 14.51 | 13.71 | 12.69 | ··· |
| 109718 | 48 47.3 | 45 57.4 | 14.64 | 14.26 | 13.94 | 13.45 | 13.47 | 13.39 | 13.26 | ··· |
| 110128 | 48 48.1 | 56 18.1 | 16.39 | 14.52 | 13.08 | 11.20 | 10.45 | 9.69  | 8.86  | 5.15 |
| 113404 | 48 0.4  | 20 37.2 | ··· | ··· | ··· | 11.96 | 11.13 | 10.23 | 9.32  | ··· |
| 117316 | 49 4.1  | 20 2.4  | ··· | ··· | ··· | 15.01 | 14.25 | 13.55 | 12.58 | ··· |
objects. This demonstrates that our sample is constituted by genuine variables, whose variation cannot be ascribed to any other phenomenon not related with the source itself.

4. RESULTS AND DISCUSSION

4.1. Location of the Variable Sources

Some or all of the 47 selected sources could in principle be foreground or background objects not related to the young population of VMR-D. In Figure 1, the location of these sources, with respect to the distribution of the molecular gas, is shown. Most of them are seen to be distributed near the IR clusters, or near the peaks of the warm gas. We take this as confirmation that we are really tracing a young population of variable sources in VMR-D. In the Table 3 (Column 2), a flag is given for each object indicating whether it lies outside the CO contours (O), inside (I), or exactly within the peaks (P). We use this information to build up a decision table which will help to clarify the nature of the sources and provide a summary of all the evidences from our analysis. The aim of this approach is to investigate to what extent our sample presents characteristics similar to those of known EXor’s, as derived from our previous studies (L07, L09) and here adopted as typical drivers for selecting disk accreting objects.

4.2. Contamination

In addition to the morphological analysis above, we have applied more quantitative tools to separate the YSOs from the remainder of the sources in the map. Main-sequence stars and background galaxies can easily be recognized in the [8.0] versus [4.5]–[8.0] diagram (e.g., Harvey et al. 2006), reported in Figure 5. Here the 47 variables are indicated with dots if observed in both of the two bands or with triangles if they have remained undetected at 8.0 μm, in which case we have considered the 3σ upper limit.

In this diagram, the YSOs occupy the open triangle on the top right side, while the photospheres are located to the left of the vertical line (at [4.5]–[8.0] = 0.5) and the galaxies (whose locus has been established by the SWIRE ELAIS-N1 extragalactic survey, Rowan-Robinson et al. 2004) on the bottom right side (e.g., Jørgensen et al. 2006; Porras et al. 2007). Noticeably, the majority of the sources detected in both the two bands or with triangles if they have remained undetected at 8.0 μm, in which case we have considered the 3σ upper limit.
Similarly, sources with [4.5]–[8.0] < 0.5 have been flagged as photospheres (PHT).

A harder class of objects to identify is the asymptotic giant branch (AGB) stars, that are long period variables (LPVs) of Mira semi-regular, or irregular type, and which represent an important fraction of the population of variables sources in the plane of the Galaxy. As shown by Marengo et al. (2008), AGBs are sources with IR excesses easily detectable by IRAC. However, in the IRAC bandpasses they have numerous molecular absorption features whose strengths and transition frequencies depend on both their chemistry (essentially the atmospheric C/O ratio) and mass loss rates. Such features can strongly affect their IRAC colors, nominally expected to be those of reddened photospheres, and make them to appear very similar to those of YSOs. The timescale of AGB (Mira) variability is roughly comparable to that of EXor’s, and as a result the time elapsed between our two epochs is not helpful in separating AGB stars from YSOs.

The spatial distribution of our 47 sources by association with the molecular cores reduces the contamination by AGB stars, which are not expected to cluster in star-forming regions; nevertheless, some additional attempts deserve to be done to estimate how the AGB contamination affects our sample. To this end, we have constructed three two-color diagrams ([3.6]–[4.5]) versus [5.8]–[8.0], [4.5]–[5.8] versus [5.8]–[8.0] and [3.6]–[4.5] versus [3.6]–[8.0]), marking on them the AGB loci as derived in Marengo et al. (2008). Then, we flagged as potential AGB’s all the sources that simultaneously fall inside the 3 AGB’s loci (or are in the close proximity to the contours) defined for each plot.

Very recently, Robitaille et al. (2008) have carefully investigated the issue of separating AGBs and YSOs, and provide specific criteria for characterizing each class with IRAC and MIPS 24 μm photometry. One of these is that sources with [8.0]–[24] < 2.5 are candidate AGB stars, while those with [8.0]–[24] > 2.5 are classified as YSOs. This means that sources with no MIPS

Table 3
Coded Photometric Properties of the Selected Sources

| Id. | Location | YSO vs. Other | Δmag | [3.6]–[4.5] | [3.6]–[8.0] | L_{IRAC} (L_{⊙}) |
|-----|----------|---------------|------|------------|------------|----------------|
| 16186 | IRS16 | YSO | C | 0 | 0.7 | 0.004 |
| 17825 | IRS16 | YSO | D | 1 | 4.1 | 0.101 |
| 18018 | IRS16 | YSO | C | 0 | 1.2 | 0.008 |
| 18177 | IRS16 | YSO | D | – | 20.0 | 0.072 |
| 24218 | I | AGB/XGAL | D | – | 1.0 | 0.001 |
| 24291 | I | PHT | D | – | 1.0 | 0.001 |
| 29062 | O | XGAL | C | 0 | 1.7 | 0.001 |
| 34166 | O | YSO | C | 0 | 1.5 | 0.009 |
| 36255 | I | PHT/AGB | C | 0 | 1.0 | 0.037 |
| 39530 | P | XGAL | I | + | 2.0 | 0.002 |
| 39917 | P | PHT | D | – | 1.0 | 0.001 |
| 44550 | I | YSO | C | – | 3.0 | 0.015 |
| 47193 | I | PHT | I | + | 1.0 | 0.001 |
| 47598 | I | YSO | C | 0 | 1.5 | 0.003 |
| 47850 | P | YSO | C | 0 | 4.6 | 0.011 |
| 48734 | I | PHT | I | 0 | 2.4 | 0.006 |
| 48885 | P | YSO | D | – | 3.0 | 0.003 |
| 50748 | P | YSO | D | – | 56.0 | 0.107 |
| 55759 | O | AGB | I | + | 1.5 | 0.009 |
| 62042 | I | PHT | I | + | 1.0 | 0.001 |
| 67878 | P | YSO | D | – | 6.5 | 0.038 |
| 68183 | I | PHT | D | – | 1.2 | 0.001 |
| 84520 | I | YSO | C | 0 | 2.2 | 0.011 |
| 85679 | I | AGB | D | 0 | 2.6 | 0.045 |
| 90096 | I | PHT | I | 0 | 1.0 | 0.002 |
| 91538 | O | PHT/AGB | D | + | 1.7 | 0.003 |
| 107546 | P | YSO | D | – | 1.8 | 0.009 |
| 109118 | I | YSO | D | – | 6.6 | 0.003 |
| 109718 | I | PHT/AGB | D | 0 | 1.2 | 0.004 |
| 110128 | I | YSO | D | – | 16.0 | 0.072 |
| 113404 | I | XGAL | I | + | 1.0 | 0.001 |
| 117316 | P | XGAL | D | – | 2.0 | 0.002 |
| 120700 | P | PHT | I | 0 | 2.9 | 0.099 |
| 120962 | P | YSO | C | – | 50.0 | 0.096 |
| 121029 | P | YSO | I | 0 | 3.0 | 0.004 |
| 121860 | P | YSO | C | – | 2.7 | 0.008 |
| 124521 | I | YSO | C | 0 | 20.0 | 0.020 |
| 124631 | P | YSO | C | 0 | 5.0 | 0.008 |
| 128081 | I | YSO | D | – | 4.6 | 0.029 |
| 127307 | O | YSO | C | 0 | 1.5 | 0.003 |
| 128958 | I | PHT | C | – | 4.8 | 0.016 |
| 131204 | O | XGAL | D | 0 | 2.0 | 0.002 |
| 131555 | I | YSO | D | 0 | 2.0 | 0.004 |
| 133791 | I | YSO | D | 0 | 2.7 | 0.022 |
| 142209 | P | YSO | C | – | 42.0 | 0.033 |
| 154688 | O | AGB | D | – | 2.4 | 0.022 |
| 155299 | O | YSO | C | 0 | 5.9 | 0.064 |

Notes.

a In bold face, the candidate young variables are indicated.

b O = outside the CO contours, I = inside, P = on a peak of warm gas.

c D = decreasing, C = constant, I = increasing.

d = redder, 0 = constant, + = bluer color during a fading event.

e Ratio of the observed SED and the underlying normalized K5-M5 photosphere, both integrated from J to 8 μm.

f Denotes that the source lies within the IR cluster IRS16, although located outside our CO map.

Figure 5. Color–magnitude diagram of the 47 selected variables. In this diagram YSOs are located between the lines [4.5]–[8.0]>0.5 and [8.0]–[24] < 14–([4.5]–[8.0]), i.e., the open triangle at the top right. Dots represent objects detected in both considered bands; triangles indicate the upper limits at 8.0 μm; therefore they should imagined to point toward the bottom left corner of the figure. We have labeled the sources which lie outside the region occupied by YSOs, also flagged as extragalactic (XGAL) or photospheres (PHT) in Table 3. The arrow shows the effect of the extinction for AV = 50 mag.
how the IR colors alone, without any further evaluation, can lead to possible misidentifications and (2) that near-IR spectroscopy is an effective means of refining the identifications based on IRAC/MIPS colors alone.

### 4.3. IRAC Colors

The EXor’s monitored so far in the near-IR (1–2.5 μm) present two main photometric characteristics (L07): (1) as most intrinsic variables, they become bluer during the outburst and redder while they fade; (2) the amplitude of the variations decrease with increasing the wavelength. These conclusions are based on observations of well-defined variability events, namely, those where the full amplitude of the variation is Δmag ≳ 1 mag, and not to marginal fluctuations usually associated with randomly sampled events. During the outburst phase, a peak at a relatively high temperature becomes more and more evident (blueing), while marginal fluctuations can be ascribed to colder contributions typical of a disk temperature stratification. In the present sample, Δmag ≳ 1 variations are quite rare (see Figure 4). Nevertheless, with the above mentioned caveat in mind, it is useful to search our sample for some similarities (or differences) with known EXor’s, since here the lack of a systematic monitoring is compensated by approaching a large and unbiased sample in a statistical sense. To that end, we present in Figures 7(a) and (b) the magnitude difference [mag(epoch1) − mag(epoch2)] as a function of the wavelength, with variations measured between the first and the second epochs, while Figures 8(a) and (b) depict the [3.6]–[4.5] versus [4.5] color–magnitude plots of the selected sources.

From the data shown in these figures some conclusions can be derived.

1. From Figures 7(a) and (b) we see that in 21 cases (representing ~45% of the total sample) the object’s amplitude decreases with increasing wavelength, as is typical of the monitored EXor’s; 17 cases (~35%) show comparable variability at all wavelengths; while for the remaining nine sources (less than 20%) the variation appears to increase with wavelength. Noticeably, just one of these latter objects is classified as a YSO by means of the color–color and color–magnitude diagrams. These results are summarized in Column 4 of Table 3 with the following codes: D (decreasing), C (constant), I (increasing). They confirm that, for the majority of sources (38 out of 47), IRAC variability is consistent with that displayed by EXor’s.

2. Irrespective of the source brightness (from 15 to 10 mag at 4.5 μm, see Figures 8(a) and (b)) the amplitude of the [3.6]–[4.5] color variation is substantially similar (≲ 0.2 mag) for sources whose color lies in the range 0.0–1.0 mag (with only seven exceptions of redder color).

3. As mentioned above, intrinsic variables in the near-IR tend to show redder and redder colors while becoming fainter, although this conclusion can only be univocally applied to sources with large fluctuations. The opposite (i.e., the colors become bluer), happens when the source becomes brighter. With reference to Figures 8(a) and (b), both these variation modalities translate into a negative slope of the line connecting the two data points. This information is also listed in Column 5 of Table 3, coded as −, 0, + to indicate a negative, null or positive slope of this line. The majority of sources (37 out of 47) are fully compatible with known EXor behavior, i.e., are coded as − or 0.
4.4. Spectral Energy Distributions

We obtained the spectral energy distributions (SEDs) for the 47 selected variables by identifying counterparts at both shorter and longer wavelengths when possible. To identify possible counterparts in the $JHK$ bands, we used the 2MASS catalog (Cutri et al. 2003), looking for matches within a radius of 2″. We identified 21 sources with a valid 2MASS detection, and the corresponding $JHK$ magnitudes are given in Table 2. We also searched the literature (Massi et al. 2000) for $JHK$ images at a better sensitivity (magnitude limit is $K \sim 18$) than 2MASS, but, unfortunately, none of them overlaps the regions with the selected variables. In the view of a future spectroscopic followup, we have also searched for optical counterparts: the positive detections are listed in the notes of Table 2. To search for longer wavelength counterparts, we used the IRAS Point Source Catalog, the Midcourse Space Experiment (MSX) catalog (Price et al. 2001), and our MIPS catalog (Giannini et al. 2007). No association was found to any of our 47 sources in the former two, to within a radius of 20′, while 24 μm MIPS counterparts were found in only 13 cases using a search radius of 6′ (also

---

**Figure 7.** Magnitude variation of the 47 sources in the two epochs, $\Delta \text{mag} = [\text{mag}(\text{epoch}1) - \text{mag}(\text{epoch}2)]$, as a function of the observed wavelength.

**Figure 8.** Observed color [3.6]–[4.5] vs. [4.5] mag of the 47 selected sources in both epochs. Black (red) dot refers to the first (second) epoch. (A color version of this figure is available in the online journal.)
listed in Table 2). Only two of our sources (namely, \# 121029 and 124521) have a 70 \( \mu m \) counterpart in a search radius of 20\(^{\prime}\); however, the multiplicity of the IRAC sources in the MIPS 70 \( \mu m \) beam implies that these associations are not unique, and we do not consider them in the following analysis. Statistically, 50% of the IRAC selected variables possess a near-IR counterpart, 30% have a 24 \( \mu m \) one, and about 20% have both.

Figures 9(a) and (b) show the SEDs of the 47 variable sources, from 2MASS wavelengths to MIPS 24 \( \mu m \) (when available). The IRAC fluxes from both epochs are shown in different colors; black dots represent the complementary photometry from different periods. Open squares indicate IRAC and MIPS 3\( \sigma \) upper limits. For comparison, a median stellar photosphere in the spectral range K5–M5 is also plotted in each panel (Hernández et al. 2007), normalized to the flux corresponding to the shortest infrared wavelength available, namely J or 3.6 \( \mu m \) (this latter for the sources without a 2MASS counterpart). The last two panels show the SEDs of UZ Tau E and V1647 Ori: the first one (Hartmann et al. 2005) is a well-known and quite unex- tincted nearby EXor, while the second is a more embedded (and maybe more massive) candidate observed with Spitzer/2MASS during an outbursting phase (Muzerolle et al. 2005). These distributions, that appear to be fully consistent with that expected for accretion disks (e.g., D’Alessio et al. 1999), can be used as a working template for comparing the SEDs of our selected variables, and for identifying among them the most likely accreting YSO candidates. By examining the SEDs of our variables, we can identify some objects as a late-type photosphere; others show an excess (more or less pronounced) at increasing wavelengths, that is typical of a temperature stratification due to the presence of an evolved circumstellar disk or envelope. We define, as a quantitative indicator, the ratio \( \mathcal{E} \) between the observed SED and the underlying median K5–M5 photosphere, both integrated from J to 8.0 \( \mu m \). For UZ Tau E and V1647 Ori, we obtain \( \mathcal{E} = 2.3 \) and 26.8, respectively. Therefore, we conservatively suggest that accreting YSO candidates are those objects with \( \mathcal{E} > 1 \). The result of such a criterion is seen in Table 3 (Column 6), and can be summarized by saying that more than 50% of the 47 selected variables present a SED compatible with an accretion disk. We notice that none of the objects with \( \mathcal{E} > 1 \) simultaneously presents IRAC fluxes compatible with a photosphere and a MIPS excess: this implies that possible binary systems composed by a variable photospheric object and a colder companion do not contaminate our sample.

The shapes of the SEDs also suggest that a non-negligible fraction of the luminosity is emitted at wavelengths longer than those probed with our observations. Consequently, we cannot give a reliable estimate of the bolometric luminosity. The absolute values of the luminosities in the IRAC range \( (L_{\text{IRAC}}, \text{last column of Table 3}) \) are, on average, remarkably low (from thousands to tenths of one solar luminosity) when compared with the IRAC estimated luminosities of known eruptive variables (7.9 and 0.4 \( L_{\odot} \) for V1647 Ori and UZ Tau, respectively). Given the high sensitivity of IRAC, this circumstance is not surprising, since, having observed VMR-D just twice without performing a systematic monitoring, we sample primarily the numerous, low luminosity end of the stellar distribution in the cloud. The luminosities obtained in both epochs differ from each other by between 15% and 50% (with a few larger exceptions). Such variations are consistent with \( M \) fluctuations within a factor 2–4, exactly the values expected over these timescales (L09).

Figure 9. (a) SEDs of sources as numbered in Table 2. IRAC fluxes observed in the first (second) epoch are depicted as green (red) dots. When available, 2MASS fluxes are also plotted for completeness although obtained about seven years prior to the Spitzer advent. MIPS fluxes (at 24 \( \mu m \)) are also not strictly simultaneous to IRAC ones. 2MASS and MIPS 24 \( \mu m \) fluxes are plotted as black dots, while open squares indicate 3\( \sigma \) upper limits. Dashed line represents a median photosphere of stars in the spectral range K5–M5. As indicated by the ordinate label, all the data are normalized to the flux corresponding to the shortest available wavelength, namely J or 3.6 \( \mu m \) (this latter for the sources without a 2MASS counterpart). (b) SEDs of V1647 Ori and UZ Tau are shown in the last two panels for comparative purposes.

(A color version of this figure is available in the online journal.)

As anticipated in Section 4.2, several M-type red dwarf stars displaying emission lines (dMe) are expected in the foreground of VMR-D, given its distance at about 700 pc. These dMe stars
4.5. Analogies with Known Eruptive Variables

Having now accumulated in Table 3, a range of independent markers for EXor behavior, or more simply of active T Tauri stars, we can now scrutinize these indicators in a systematic way in an attempt to identify the variables that behave as the young accretors do: namely, those that simultaneously present all the characteristics summarized in the last line of Table 3 and discussed in the previous Sections. After analyzing in this way each of the sources in Table 3, we conclude that 19 (boldfaced) sources out of 47 manifest the same five flags we argue are typical of EXor’s: P(I), D(C), YSO, −(0), and >1.0. Hence, we identify these 19 as the accreting protostars candidates emerging from the present study. In particular, six of them have the same flags strictly (P, D, YSO, −, >1.0). Out of the remaining 29 sources, another 10 show four flags in accordance with the template, while 19 sources have three or fewer identifying flags.

From an evolutionary point of view, protostars can be classified according to the value of the spectral index computed from 2 to 10 \( \mu m \) (Greene et al. 1994); however the classification scheme does not change substantially if computed up to fluxes of 20–25 \( \mu m \) (e.g., Rebull et al. 2007). Among the final 19 objects, 10 are detected at 24 \( \mu m \). Of these, three are Class I (17825, 44510, 50748), five are flat spectrum (67870, 84520, 107546, 110128, 125801), and two are Class II sources (131555, 133791). This indicates that the accreting flaring stage may occur earlier than the Class II phase, at least in the framework of an evolutionary scenario. For comparison, L07 have classified two EXor’s as Class I sources (NY Ori and PV Cep), three as flat spectrum sources (AZ Tau, V1143 Ori and EX Lup), and four as Class II (UZ Tau, VY Tau, DR Tau, and V1118 Ori). For the remaining nine sources, we computed the slope of the SED up to the longest wavelength available (typically 8 \( \mu m \)) and consistent with the 24 \( \mu m \) upper limit. In this way, we find that three and six sources are compatible with (or older than) flat and Class II sources, respectively.

Our demography of the VMR-D cloud (F. Strafella et al. 2009, in preparation) provides a total of 487 YSOs made up of Class I (62), flat spectrum (92) and Class II (333) objects. It is remarkable that in addition there are 171 Class III sources associated to the VMR-D. Because variables that were in quiescence during the epochs of our monitoring are missed by the present selection, we cannot reasonably attempt to estimate the duration of the intense disk accretion phase with respect to the entire PMS lifetime. We can, however, conclude that: (1) by adopting our empirical approach, about 50% of the selected variables are potential active T Tauri stars or EXor candidates deserving of further study (mainly IR monitoring and spectroscopy); (2) a value of 4% is a lower limit on the percentage of accreting variables with respect to the total protostars (from Class I to Class II sources) in VMR-D; (3) an important fraction of these 19 candidates is constituted by objects with Class I and flat spectra, a trend opposite to the young stellar population in VMR-D which, on the contrary, is dominated by Class II and III sources. This circumstance might stem from our requirement that our candidates are requested to be associated with CO peaks or filaments: this results in finding more embedded and younger objects. Moreover, the need for a detectable excess (\( \mathcal{E} \) flag) goes in the same direction.

5. CONCLUDING REMARKS

We present a catalog of objects identified as probable PMS variables, obtained by comparing two IRAC images of the star-forming region VMR-D separated by six months. By analyzing the results, we reach the following conclusions.

1. The same selection criteria were applied to the data set of both epochs aiming to find real detections (by removing spikes and artifacts) with genuine variations (well above the photometric errors). Recorded flux fluctuations span from 10% to more than 100%.

2. Variability in the first two IRAC bands (3.6 and 4.5 \( \mu m \)) identifies more than twice as many objects than does variability in bands 3 and 4 (5.8 and 8.0 \( \mu m \)).

3. Forty-seven variable objects have been identified (out of a total of 170,000 sources). We estimate the possible contamination of the sample by considering extraneous galactic or extragalactic sources by using the well-defined properties of active stars (or EXor type) with recurrent disk accretion phenomena as templates.

4. SEDs were constructed from near- to mid-IR for all the 47 sources. IRAC luminosities are remarkably low (from thousandths to tenths of one solar luminosity), but this is not surprising since, having observed the region just twice without performing a systematic monitoring, we likely sample the low luminosity end of the stellar distribution.

5. Nineteen sources from our full sample of 47 have all the same properties that characterize known EXor objects. They are potential accretion flaring or EXor candidates and deserve further studies (mainly IR monitoring and spectroscopy) to better characterize their nature. In this latter respect, we note that the brightness of the selected variables is well compatible with the sensitivity of the current infrared spectroscopic instrumentation.

6. A significant number (i.e., eight sources) of the final 19 candidates are recognizable as Class I and flat spectrum sources (with two Class II objects). This suggests that the accretion flaring or EXor stage might come as a Class I/II transition.

7. New prescriptions are derived from our analysis that can facilitate identifying accretion variables in large IR database.

The authors thank Arkady A. Arkharov and Valeri M. Larionov for providing them with the near IR spectra of the sources win35 and win70, taken at Campo Imperatore (Italy). This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407. Support for the IRAC instrument was provided by NASA under contract number 1256790 issued by JPL.
REFERENCES

Cutri, R. M., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release (Pasadena, CA: Caltech)
D’Alessio, P., Calvet, N., Hartmann, L., Lizano, S., & Cantó, J. 1999, ApJ, 527, 893
De Luca, M., et al. 2007, A&A, 474, 863
Elia, D., et al. 2007, ApJ, 655, 316
Fazio, G. G., et al. 2004, ApJS, 154, 10
Jørgensen, J. K., et al. 2006, ApJ, 645, 1246
Giannini, T., et al. 2005, A&A, 433, 941
Giannini, T., et al. 2007, ApJ, 671, 470
Greene, T. P., Wilking, B. A., Andrè, P., Young, E. T., & Lada, C. J. 1994, ApJ, 434, 614
Hartmann, L., & Kenyon, S. 1985, ApJ, 299, 462
Hartmann, L., & Kenyon, S. 1996, ARA&A, 34, 207
Hartmann, L., et al. 2005, ApJ, 629, 881
Harvey, P. M., et al. 2006, ApJ, 644, 307
Herbig, G. H. 1989, in Proc. of the ESO Workshop on Low-Mass Star Formation and Pre-Main Sequence Objects, ed. B. Reipurth (Garching: ESO), 233
Herbig, G. H. 2007, AJ, 133, 2679
Hodapp, K. W. 1999, AJ, 118, 1338
Hodapp, K. W., et al. 1996, ApJ, 468, 861
Köppä, Å., et al. 2007, A&A, 470, 211
Lorenzetti, D., et al. 2002, ApJ, 564, 839
Lorenzetti, D., et al. 2006, A&A, 453, 579
Lorenzetti, D., et al. 2007, ApJ, 665, 1182 (L07)
Lorenzetti, D., et al. 2009, ApJ, 693, 1056 (L09)
Marengo, M., Reiter, M., & Fazio, G. G. 2008, in AIP Conf. Proc. 1001, IXth Torino Workshop on Evolution and Nucleosynthesis in AGB stars and the 2nd Perugia Workshop on Nuclear Astrophysics, ed. R. Guandalini, S. Palmerini, & M. Busso (Melville, NY: AIP), 331
Massi, F., Lorenzetti, D., & Giannini, T. 2003, A&A, 399, 147
Massi, F., Lorenzetti, D., Giannini, T., & Vitali, F. 2000, A&A, 353, 598
Massi, F., et al. 1999, A&AS, 136, 471
Massi, F., et al. 2007, A&A, 466, 1013
Muzerolle, J., et al. 2005, ApJ, 620, 107
Porras, A., et al. 2007, ApJ, 656, 493
Price, S. D., Egan, M. P., Carey, S. J., Mizuno, D. R., & Kuchar, T. A. 2001, AJ, 121, 2819
Rebull, L. M., et al. 2007, ApJS, 171, 447
Reipurth, B., & Aspin, C. 2004, ApJ, 606, L119
Riaz, B., Muller, D. J., & Grizis, J. E. 2006, ApJ, 650, 1133
Ricke, G. H., et al. 2004, ApJS, 154, 24
Robitaille, T. P., et al. 2008, AJ, 136, 2413
Rowan-Robinson, M., et al. 2004, MNRAS, 351, 1290
Sicilia-Aguilar, A., Merín, B. T., Hornuth, F., & Abrahám, P. 2008, ApJ, 673, 382
Schuster, M. T., Marengo, M., & Patten, B. M. 2006, AAS, 209, 8420
Shu, F. H., et al. 1994, ApJ, 429, 781
Stetson, P. B. 1987, PASP, 99, 191
Werner, M. W., et al. 2004, ApJS, 154, 1
Winston, E., et al. 2007, ApJ, 669, 493
Winston, E., et al. 2009, AJ, 137, 4777