Abstract. We present results of an ongoing survey of low surface brightness planetary nebulae (PNe). Using both narrow-band imaging and long slit spectroscopy we have studied 15 new examples for interaction with the interstellar medium (ISM) demonstrating that this process is common in evolved PNe. Characteristic properties of the nebulae in terms of morphology and plasma parameters have been established and different degrees of interaction can be identified. Although the study of the objects is at an early stage the observational findings are in agreement with theory. The data indicate that the objects have a very high degree of individuality due to the action of complex physics under varying conditions.

1. Introduction

Many aspects of the physics and shapes of PNe can successfully be explained in terms of the two-wind model by Kwok, Purton, & Fitzgerald (1978) as the product of the mass-loss history of the star on the asymptotic giant branch (AGB) and during the central star evolution. Our observations indicate that at some point in the evolution of PNe other factors may become very important for the further development, and for such objects the two-wind paradigm may break down. Old PNe interacting with the ISM are a case in point. This work has implications for a hitherto neglected aspect of PNe: they give evidence for an important process that remains very difficult to study; the return of processed nuclear matter to the ISM. This material leads to the chemical evolution of galaxies. Old PNe in decay are the very last objects that can be observed before the nebular material is fully dispersed and mixes with the ISM.
Actually this is one of the very few methods to study the properties of the ISM directly, in this sense PNe can act as a probe performing an active experiment on the ISM.

2. The observations

Earlier work on interacting PNe by Tweedy & Kwitter (1996) and Xilouris et al. (1996) has given us images of a sample of very large (5 to 20 arcmin in diameter) PNe at an angular resolution of about 5 arcsec. In our survey (Kerber 1998) we have concentrated on high resolution imaging of smaller (< 5 arcmin) PNe combined with long slit spectroscopy.

| Name       | Identification   | $\alpha$ (2000.0)         | $\delta$ (2000.0)     |
|------------|-----------------|---------------------------|------------------------|
| KLW 11     | PN G193.0 − 04.5| $05^h 57^m 08^s$          | $+15^\circ 25' 31''$  |
| KLW 12     | PN G197.0 + 05.8| $06^h 43^m 26^s$          | $+16^\circ 48' 53''$  |
| EGB 9      | PN G209.4 + 09.4| $07^h 19^m 01^s$          | $+07^\circ 23' 17''$  |
| KeWe 3     | PN G238.4 − 01.8| $07^h 33^m 25^s$          | $-23^\circ 25' 44''$  |
| MeWe 1-1   | PN G272.4 − 05.9| $08^h 53^m 37^s$          | $-54^\circ 05' 08''$  |
| NeVe 3-1   | PN G275.9 − 01.0| $09^h 34^m 01^s$          | $-53^\circ 11' 59''$  |
| Lo 4       | PN G274.3 + 09.1| $10^h 05^m 46^s$          | $-44^\circ 21' 33''$  |
| MeWe 1-2   | PN G283.4 − 01.4| $10^h 14^m 24^s$          | $-58^\circ 11' 49''$  |
| NeVe 3-6   | PN G292.5 + 00.9| $11^h 25^m 43^s$          | $-60^\circ 14' 30''$  |
| KFR 1      | PN G296.3 + 03.1| $12^h 00^m 14^s$          | $-59^\circ 04' 34''$  |
| HaTr 1     | PN G299.4 − 04.1| $12^h 16^m 33^s$          | $-66^\circ 45' 46''$  |
| WeKG 2     | PN G308.4 + 00.4| $13^h 38^m 42^s$          | $-61^\circ 55' 45''$  |
| SuWt 1     | PN G309.2 + 01.3| $13^h 43^m 59^s$          | $-60^\circ 49' 42''$  |
| MeWe 2-4   | PN G314.0 + 10.6| $14^h 01^m 15^s$          | $-50^\circ 40' 12''$  |
| MeWe 1-4   | PN G315.9 + 08.2| $14^h 17^m 30^s$          | $-52^\circ 26' 19''$  |
| LoTr 10    | PN G316.3 − 01.3| $14^h 46^m 20^s$          | $-61^\circ 13' 30''$  |
| Lo 10      | PN G328.2 + 01.3| $15^h 49^m 29^s$          | $-52^\circ 30' 17''$  |
| K 1-31     | PN G335.4 + 09.2| $15^h 53^m 13^s$          | $-41^\circ 50' 25''$  |
| HaTr 3     | PN G333.4 − 04.0| $16^h 39^m 38^s$          | $-52^\circ 49' 11''$  |
| KeWe 5     | PN G348.9 + 04.6| $16^h 57^m 56^s$          | $-35^\circ 24' 56''$  |
| Tc 1       | PN G345.2 − 08.8| $17^h 45^m 35^s$          | $-46^\circ 05' 23''$  |

Table 1. List of low surface planetary nebulae studied in this work

We have collected the largest, homogeneous data set on old PNe interacting with the ISM for study of the physical properties of these objects. In Table 1 our sample is summarized. A more detailed description of the observations and some individual objects can be found in Rauch et al. (2000 this volume).
3. Observational Results

In our sample of 21 low surface brightness PNe we have found signs of interaction with the ISM in 15 cases. This unexpectedly large percentage may be the result of an observational bias: the interaction leads to a – usually asymmetric – brightness enhancement in these low surface brightness objects facilitating their discovery, or to put it differently: some of the nebulae may not have been discovered if it had not been for the interaction with the ISM.

For at least five of these 15 PNe the central star has been found to be displaced from the geometrical center indicating a very advanced stage of interaction. Combined with the fact that the spectroscopically derived electron densities are low in all cases and very low for most of the objects (Tab. 3), this is clear evidence that the interaction is common in evolved PNe. Using long-slit spectroscopy we have for the first time been able to characterize the plasma parameters of these nebulae demonstrating that the interaction regions usually show an increased electron density and – in most cases – a pronounced enhancement of the low-ionization stages. The [N\textsc{ii}]/H\textsc{α} ratios show absolute values of 1 to 4 with one example reaching 12 and increase by factors of up to 3.5 compared with the inner parts of the nebulae which are not affected by the interaction. A correspondingly lower excitation class is also observed.

By combining both imaging and spectroscopy, we are therefore able to diagnose the degree of interaction.

All of the above is consistent with the current theoretical understanding of the interaction process as described by Borkowski, Sarazin, & Soker (1990), Soker, Borkowski, & Sarazin (1991) and Dgani (2000 this volume). A schematic description of the interaction process can be found in Rauch et al. (2000).

| Nebula  | Diameter ″       | Ratio of axes | Decentral. central star | Asymm. shape | Sign of instability |
|---------|------------------|---------------|-------------------------|--------------|---------------------|
| EGB 9   | 377×234          | 0.62          | ?                       | ++           | ++                  |
| KeWe 3  | 283×306          | 0.92          | ?                       | ++           | ++                  |
| MeWe 1-1| 143×165          | 0.87          | +                       | ++           | +                   |
| NeVe 3-1| 62×53            | 0.85          | ?                       | ++           | ++                  |
| MeWe 1-2| 272×256          | 0.94          | +                       | +            | +                   |
| KFR 1   | 90×100           | 0.9           | +                       | ++           | ++                  |
| HaTr 1  | 76×73            | 0.96          | ?                       | ++           | −                   |
| SuWt 1  | 94×53            | 0.56          | ?                       | ++           | −                   |
| MeWe 2-4| ∼ 480           | ∼ 1           | ++                      | ++           | +                   |
| MeWe 1-4| 113×148          | 0.76          | ++                      | ++           | ++                  |
| Tc 1    | 57               | 1             | +                       | −            | ++                  |

Table 2. Morphological features in some interacting PNe

Morphologically our deep high-resolution images show an enormous amount of detail and clearly show indication of instability, in some cases the nebulae are obviously in the process of being broken apart, for example see the images of MeWe 1-4 and KFR 1 in Rauch et al. (2000).

It has been shown recently by Soker & Dgani (1997) and Dgani & Soker (1998) that the effect of the interstellar medium’s magnetic field (ISMF) can be ex-
tremely important. We see evidence for the ISMF’s action in some of our objects in the form of stripes or rolls as described by Dgani (2000) in this volume.

4. Future work

In this project we have already begun to extend the sample to the northern hemisphere and have included very large objects requiring wide-field imaging. Another important aspect will be the study of the central stars giving us information on their evolutionary status, as well as the spectroscopic distance.

Acknowledgments

This work was supported by travel grants from the Austrian Ministerium für Wissenschaft, Forschung und Verkehr and the Universität Innsbruck and by the DLR under grant 50 OR 9705 5 (TR).

References

Borkowski K.J., Sarazin C.L., & Soker N., 1990, ApJ 360, 173
Dgani R., & Soker N., 1998, ApJ 495, 337
Kerber F., 1998, Rev. in Mod. Astronomy 11, ed. R.E. Schielicke, Astronomische Gesellschaft, Jena, p. 161
Kwok S., Purton C.R., & Fitzgerald P.M., 1978, ApJ 219, L125
Soker N., & Dgani R., 1997, ApJ 484, 277
Soker N., Borkowski K.J., & Sarazin C.L., 1991, AJ 102, 1381
Tweedy R.W., & Kwitter K.B., 1996, ApJS 107, 255
Xilouris K.M., Papamastorakis J., Paleologou E., & Terzian Y., 1996, A&A 310, 603

| Nebula     | n_e/cm^−3 | Excitation class | [N II] 6584 | Hα 6563 |
|------------|------------|------------------|------------|---------|
|            | inner part | interaction zone | inner part | interaction zone | inner part | interaction zone |
| EGB 9      | < 100      | 170              | 5          | 4        | 0.3       | 0.8       |
| KeWe 3     | < 100      | < 100            | 3          | 3        | 11.2      | 12.7      |
| MeWe 1-1   | < 100      | 180              | 5          | 4        | 0.8       | 2.7       |
| NeVe 3-1   | 120        | 220              | 2          | 3        | 0.8       | 2.5       |
| MeWe 1-2   | < 100      | 260              | 4          | 2        | 1.7       | 3.0       |
| KFR 1      | 250        | < 100            | 4          | 4        | 1.9       | 1.6       |
| HaTr 1     | < 100      | –                | 5          | –        | 0.5       | –         |
| SuWt 1     | 170        | 200              | 7          | 4        | 2.1       | 3.8       |
| MeWe 2-4   | –          | 390              | 6          | 5        | 0.8       | 2.7       |
| MeWe 1-4   | 470        | 120              | 6          | 3        | 0.5       | 0.8       |

Table 3. Nebular parameters from plasma diagnostics