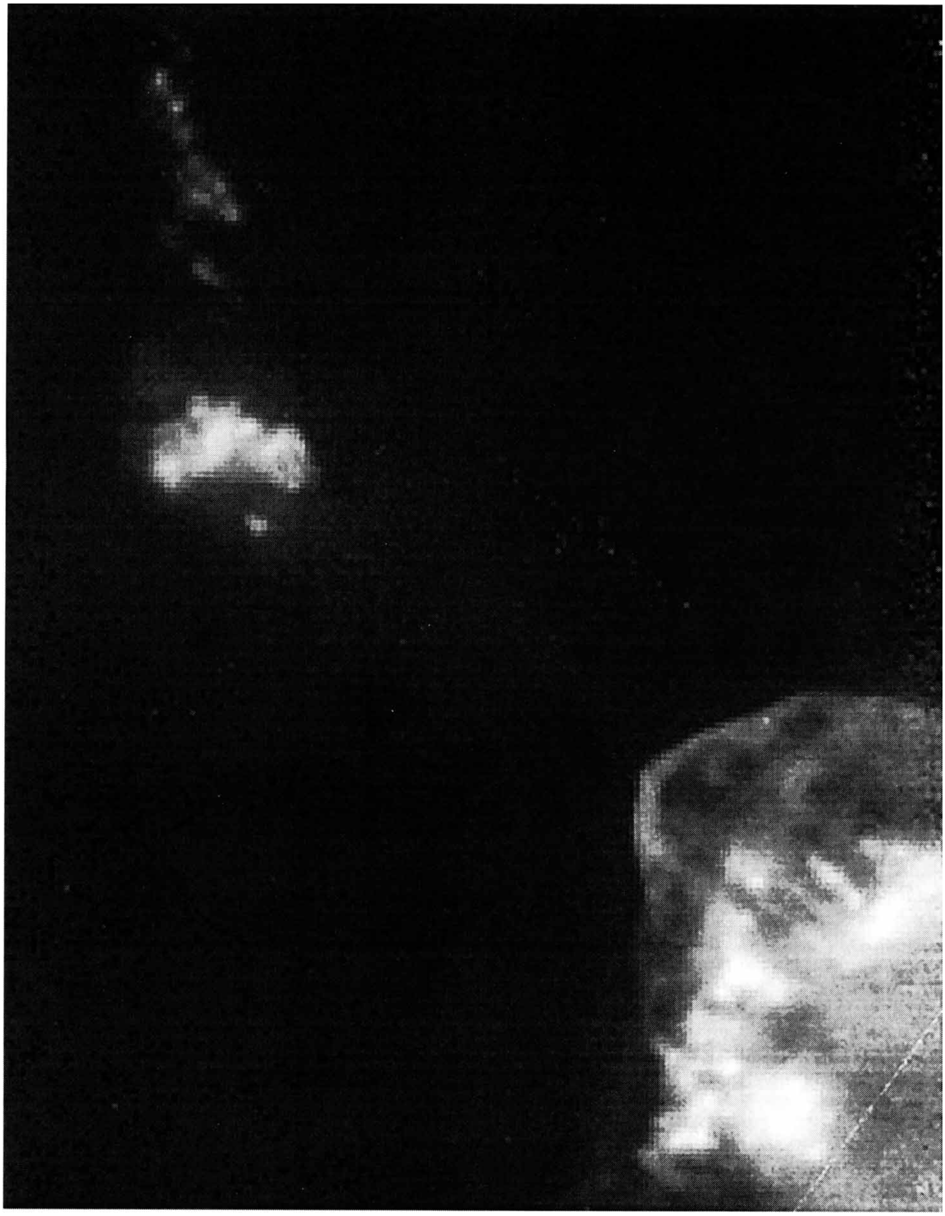
III. THE CENTRAL STARS



One of the ansae (upper left) and a portion of the inner region (lower right) of NGC 7009 observed in the Wide Field Camera of the Hubble Space Telescope in the light of [N II]658.3nm. When displayed with higher contrast, a faint bridge of emission is seen to connect the tip of the inner region to the closest ansa. The radial "streaks" of [N II] emission in the lower right are seen only in lines of low ionization. Like the caps of NGC 6543, the streaks have relatively high redshifts and thus qualify as FLIERs. Credit: *Narrowband HST Images of Microstructures in Planetary Nebulae,* Bruce Balick, J. Alexander, A. Hajian, Yervant Terzian, M. Perinotto, and P. Patriarchi.

OBSERVATIONS OF CSPN

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1. Introduction

It's a good thing that we're starting to meet every four years rather than every five. There has been tremendous progress in understanding the properties and evolution of central stars of planetary nebulae (CSPN) since the last meeting in Innsbruck in 1992. Much of the credit is due to new spectra and images obtained at observatories that weren't even in existence four years ago. Table 1 lists most of the space observatories used by astronomers reporting at this symposium. The ones marked with the asterisk are new to this conference. The double asterisks for the Hubble Space Telescope instruments remind us that the telescope was repaired in December 1993. The reference gives the identification of the poster paper given at this meeting. We can look forward to similar improvements in ground-based observatories to be reported at the next meeting.

TABLE 1: CSPN Observatories in Space

Observatory	**Description**	**Reference**
ISO*	infra-red imagery and spectroscopy	III-10
IUE	ultraviolet spectroscopy	
HST**/WFPC2, FOC	high-resolution imagery	
HST**/FOS, GHRS	high-resolution spectroscopy	
Orfeus*	far-UV spectroscopy	I-30
Astro2/HUT	far-UV spectroscopy	
EUVE*	Extreme ultraviolet explorer	IV-14
ROSAT	X-ray, EUV telescope	II-25

H. J. Habing and H. J. G. L. M. Lamers (eds.), Planetary Nebulae, 55–63.

With the large volume of new data, it is impossible to cover all the recent observational findings. Fortunately, there are several proceedings which describe progress in the field since 1992. They are:

Evolution of Planetary Nuclei (1993), Acta Astronomica Vol 43, pages 295-455

White Dwarfs (1993), Lecture Notes in Physics 443, eds. D. Koester & K. Werner (Springer: Berlin)

Hydrogen-Deficient Stars (1996), ASP Conference Series, Vol 96, eds. C.S. Jeffery & U. Heber

Planetary Nebulas with Wolf-Rayet Nuclei (1996), Astrophysics & Space Science, Vol. 238, eds. I. Lundstrom & B. Stenholm

The Appendices in *Hydrogen Deficient Stars* compiled by Simon Jeffery deserves special mention. They contain up-to-date, comprehensive catalogues of CSPN along with references to spectral analyses. Table 4 lists the Wolf-Rayet CSPN (57 known in the Galaxy, 6 in the LMC, 2 in the SMC); Table 5 gives the He-rich O-type CSPN (3 known); and Table 6, the PG1159 CSPN (18 known). For a similar listing on H-rich stars, see Méndez (1991).

The main result of the many, sophisticated spectral analyses is that we now have reliable parameters for central stars of *all* spectral types. We are now able to place them on the HR diagram and learn about their evolutionary status. When we do this, we find that there are two parallel sequences of CSPN – one that is hydrogen-rich at their surface, the other helium-rich – that starts well before the star is hot enough to ionize the nebulae and goes right though to the final, white-dwarf stage.

In this paper, I will take CSPN's by evolutionary phase and spectral class. I will first deal with the young, cool CSPN, and then go on to CSPN with O-type spectra and Wolf-Rayet spectra, then to the PG1159 stars and stars in transition to the white dwarf phase. I will not cover binary CSPN's, which are discussed by Livio in this session, nor CSPN in other galaxies (Session 8).

2. Young, "Cool" Central Stars

By "young and cool" CSPN, I mean those central stars that have most recently evolved off the asymptotic giant branch (AGB) and still have temperatures less than about 35,000 °K. This group consists of (i) stars with late-Of spectra (H-rich atmospheres) with signs of mass-loss and (ii) late-type WC spectra, i.e. spectra with C, O, He lines in emission indicating intense, high-velocity winds. The central star of Henize 2-131 is a good example of a late-Of-type star. Figure 1 shows portions of the ultraviolet spectrum obtained by the GHRS compared with de Koter's ISA-WIND models (de Koter et al. 1993, 1996). The strength of C III 1247 vs. C IV 1548,1550

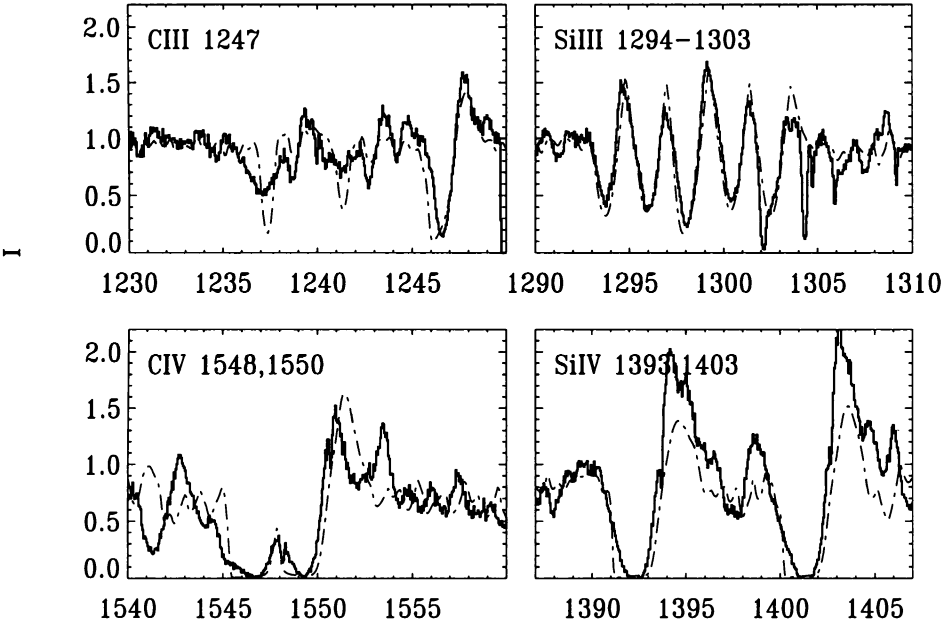

Figure 1. GHRS Observations of the Central star of He 2-131 (solid line). The parameters of the model spectrum (dash-dot) are $T_{\rm eff}$=31 kK, $\dot{M}= 4.2\times10^{-7} M_\odot$ yr^{-1} for an adopted mass, $M = 0.70 M_\odot$ (Altner & Heap 1993). The mass-loss rate was estimated from model fits to the spectrum with emphasis on the HeII λ4686 line and is sensitive to temperature.

or Si III 1300 vs. Si IV 1393,1403 fix the temperature at 31 kK. The model also gives the mass flux of the wind, i.e. the amount of material leaving 1 cm^2 of the stellar surface per unit time. To convert this quantity to a mass-loss rate requires a knowledge of the stellar radius, which then also sets the stellar luminosity and mass. Hence, the derived mass-loss rate is a function of the assumed stellar mass. Regardless of the mass assumed, the observed mass-loss rate is about twice the rate of mass “lost” due to nuclear burning. Evidently, mass-loss – not nuclear burning – presently drives the evolution of this star. The observed mass-loss rate is also 2-3 times that predicted by conventional (single scattering) radiation-driven wind theory (Kudritzki et al. 1989).

Such high mass-loss rates are of interest in that they tend to support the idea of pulsation-enhanced mass-loss in proto-CSPN and cool CSPN. According to Gautschy (1993), such stars are subject to pulsational instabilities arising from an opacity bump in the envelope ($T \approx 2 \times 10^5$ K). Since the opacity is mostly due to iron lines, the instability should grow with increasing metal content. Thus, we expect that metal-rich CSPN should show signs of pulsation-enhanced mass-loss, while metal-poor CSPN should show only the "normal" mass-loss driven by radiation pressure. This predicted effect of metallicity appears to be consistent with nebular observations (Aller & Czyzak 1983), which show that the abundances of elements *not* involved in nuclear processing, e.g. sulphur or argon, are deficient by 2-3X in O-type central stars, but have approximately solar values in Wolf-Rayet-type CSPN. Could metallicity be the key to differientiating between the O-type and WR-type CSPN?

Low-temperature CSPN also include late-type Wolf-Rayet stars, which are known to have very intense winds. Since these stars will be discussed in detail by Hamann, I will not dwell on them here, but only say that serious modelling of WR-type central stars is new since the last conference. Thanks to the work of Hillier, Hamann, and others, it is now possible to derive the basic atmospheric parameters including abundances for these stars. Ironically, the defining characteristic of WR stars — the high mass-loss rate – is the one parameter that does *not* follow directly from the models. As noted before, atmospheric models yield only the mass flux, not the mass-loss rate. A dense wind does not imply a high stellar mass or luminosity.

3. O-Type Central Stars

In previous conferences, O-type central stars were the focus of attention, because these stars have the "simplest" atmospheres. The fundamental parameters of these stars – including stellar mass – can be derived from absorption lines in the photospheric spectrum. Most of the bright O-type CSPN have already been studied and reported on at previous conferences (Kudritzki & Méndez 1993). The new news at this conference is that spectra of faint central stars are now being obtained by the Keck telescope (McCarthy et al., poster paper I-31). [It's nice to see big telescopes being put to proper use!] One very interesting object observed by both Keck and the GHRS on the Hubble Space Telescope is K648, the central star of Ps 1, which is in the low-metallicity globular cluster, M15. According to McCarthy et al. (I-32), a non-LTE analysis of the optical absorption lines in the Keck spectrum yields a $T_{\rm eff}$=43 kK and a solar carbon abundance. However, the UV spectrum of this star analyzed by Heber et al. (1993) – also using non-LTE modelling techniques, but this time taking NLTE line-blanketing into account – gives $T_{\rm eff}$=37 kK and a three times solar carbon abundance. Some of the differences are due to the use of fully line-

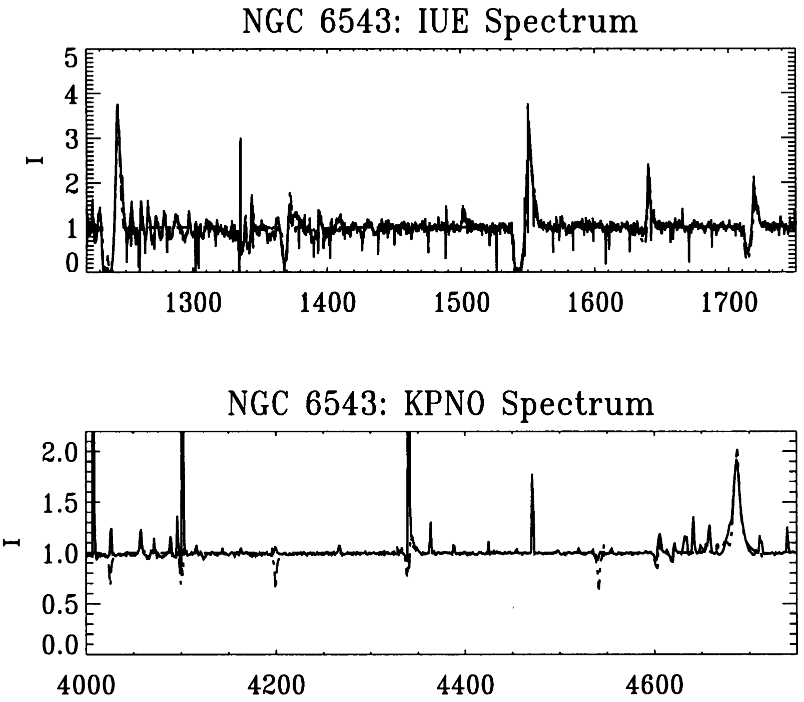

Figure 2. IUE and KPNO Echelle Spectra of NGC 6543 (solid line). The parameters of the model (dash-dot) are: T_{eff}=48 kK, $\dot{M}=1.6\mathrm{x}10^{-7}$ $M_\odot$ yr^{-1} for an assumed $M = 0.60$ $M_\odot$. From de Koter et al. (1996).

blanketed non-LTE model atmospheres which are now being constructed for hot stars (Dreizler & Werner 1993, Hubeny & Lanz 1995). However, they are apparently also due to differences from one research group to the next. Clearly such differences must be identified and resolved before we can have confidence in the derived abundunces.

Besides line-blanketed NLTE model atmospheres, the other important theoretical development is the construction of "unified" models — models which make no distinction between the photosphere and wind but treat the atmosphere as a whole. Such work is in a very active phase (c.f. Sellmaier & Pauldrach I-37) and promises reliable results for CSPN showing Of or Of/WR-type spectra. A good example is the central star of NGC 6543. Figure 2 shows de Koter et al.'s (1996) unified model of the atmosphere of this Of/WR-type central star as compared to UV (IUE) and optical (KPNO) spectra. While the model is inadequate for the deepest layers of the atmosphere where the photospheric HeII lines are formed, it gives a nice fit to the observations further out in the wind where the wind lines are formed. This star was also observed by ORFEUS in the far-UV (Zweigle, I-30).

4. Wolf-Rayet-Type Central Stars

A Wolf-Rayet star is a hot star showing an emission-line spectrum indicative of a very dense wind. WR spectra are broken down into two classes, WN or WC, depending on whether the dominant emission lines are from nitrogen or carbon. Unlike massive Wolf-Rayet stars, CSPN show only WC or WC-N spectra, which is in accord with evolutionary theory (Renzini 1983). Nevertheless, WC-type CSPN show a much broader range in temperature than do their massive counterparts – from $T_{\rm eff} \leq 30$ kK at spectral type, WC12, barely able to ionize the surrounding nebulosity (de Marco et al., I-20) to 130 kK at WC3 (Koesterke et al. I-23).

There is still the nagging problem of the distribution of spectral types and presumably, temperatures. As Méndez (1983) pointed out some time ago, there seem to be plenty of late-type WC stars and very early-type WC stars, but very few mid-type WC stars. The new catalogue of WR-type CSPN (Jeffery 1996) shows this dearth of mid-type WC stars quite clearly. See also Acker et al. (I-19).

The most unexpected result on Wolf-Rayet CSPN's comes not from spectroscopic analysis, but from "astro-seismology". Most of us had thought of WR-type CSPN's as being rather massive. Certainly, their spatial and velocity distribution in the Galaxy and their evolutionary properties seemed to support this idea. In addition, their extraordinarily dense winds seemed to suggest that they were very luminous stars approaching the Eddington limit, and hence, massive stars. Evidently, this is not always the case. According to Bond and colleagues (IV-13), the Wolf-Rayet central star of NGC 1501 is a pulsating star with a mass of only $0.55 \pm 0.03\ M_{\odot}$, which is near the lower limit for post-AGB stars.

5. Very Hot Central Stars

By "very hot", I mean VERY HOT – with effective temperatures ranging from 80,000°K to 170,000°K (Werner et al. 1996). The old dichotomy of O vs. WR spectral type still holds even at these very high temperatures. There are some CSPN, which Méndez (1991) classifies as having O(C) spectra, whose spectra look like very early O-type spectra but have abnormally strong C IV lines. There are also the WC-O VI central stars (Heap 1983), which show a Wolf-Rayet emission-line spectrum with O VI, O VII, or even O VIII emission lines (Feibelman 1996). Then there are the PG1159 stars, which are seen only at high temperatures. Their spectra show high-excitation He, C, and O lines, both in absorption and emission. Actually, we could just as well call them NGC246 stars, since this central star was the first of this class to be identified (Heap 1975).

In any case, the PG1159 stars are something of a puzzle. First, there is the question of pulsation. As Werner et al. (1996) stress, there can be two PG1159 stars at nearly the same location on the HR diagram (c.f. also Ciardello & Bond 1996). One pulsates; the other one doesn't. Why? It can't be for errors in locating a star on the HR diagram. Werner (1996) showed that spectral analysis and pulsational analysis yield virtually the same temperature and stellar mass. Second, there is the question of prior envelope ejection. There can be two PG1159 stars at similar locations on the HR diagram. One has a nebula around it, and the other one doesn't. This situation has stimulated deep imaging searches for PN around PG1159 stars, but with mostly negative results (e.g. Werner et al., IV-10). How did these stars get to their present location on the HR diagram without ejecting a nebula?

The class of very hot central stars must also include the (in)famous central star of NGC 7027. Now that the Hubble Space Telescope has been repaired, it is possible to get a picture or spectrum of the central star of NGC 7027 with negligible contamination from the nebula. Figure 3 (top) shows the stellar spectrum obtained with the Faint Object Spectrograph on HST. The emission lines are all previously identified nebular lines (Keyes & Aller 1991), but the continuum is nearly all from the star, and we can set the magnitude of the star at V=15.92, a little brighter than previous estimates from CCD imaging.

The fact that all spectral lines are nebular was totally unexpected. I had expected to see the signature of a PG1159 star – high-excitation stellar lines of CIV, OVI, OVII, etc. To investigate this matter, Hubeny recently calculated two non-LTE models of the central star: one with a PG1159 composition, the other with a solar composition, and both with T_{eff}=140 kK and log g=6.0. The solar-composition model, which shows no significant features, is compatible with the observations. The PG1159 model is not. As shown in Figure 3 (bottom), the model predicts rather strong emission of the CIV doublet at 5800, 5812 Å, which is not observed.

Despite this string of unanswered questions, one important problem in stellar evolution *does* seem to be solved. The problem was that there appeared to be a lack of very hot, hydrogen-rich stars. This led to speculation that H-rich O-type stars changed into He-rich stars when they were very hot, and then back to H-rich stars via gravitational settling as they cooled as white dwarfs. Napiwotzki (1995) and Dreizler et al. (1996, IV-14) have shown that such maneuvering is unnecessary: there are indeed some very hot, H-rich stars. As it stands, the central star of EGB1 at T_{eff}=133 kK

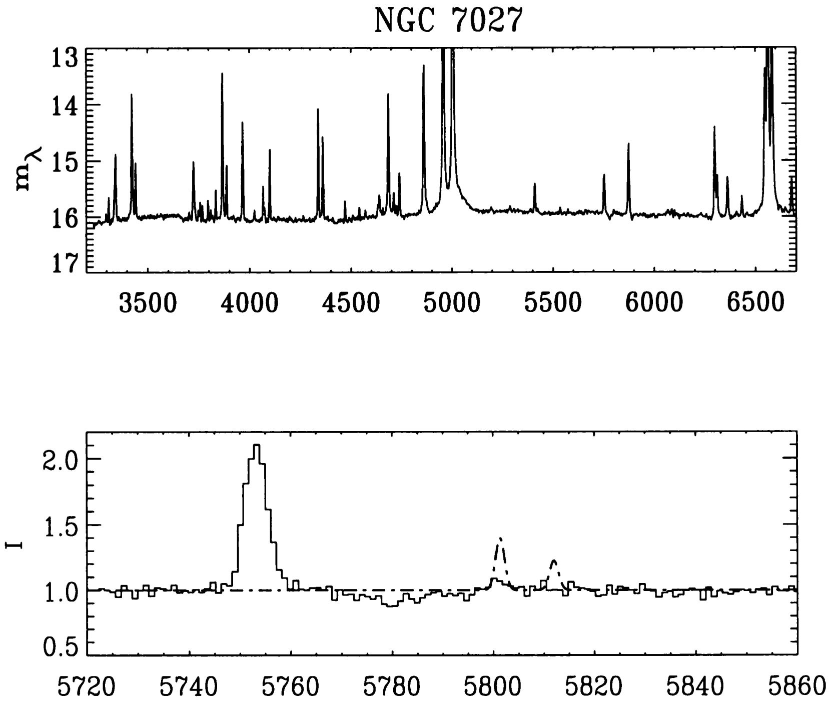

Figure 3. HST/FOS Observations of the CSPN of NGC 7027. Top: the absolute flux distribution expressed in magnitudes: $m_\lambda = 2.5 \log F_\lambda - 21.1$. Bottom: the normalized spectrum (solid) compared with a model spectrum (dash-dot) for a PG1159-type composition, $T_{\rm eff} = 140$kK, and log g=6.0. The model was computed by Ivan Hubeny using his not-LTE code, TLUSTY (Hubeny et al. 1994).

holds the record for the hottest H-rich star known.

6. Conclusions

To summarize the preceding sections, there appear to be two independent sequences of central stars. The H-rich sequence is composed of central stars with O-type spectra, the "H-rich" PG 1159 stars, and the DA white dwarfs. The He-rich sequence includes the Wolf-Rayet CSPN, the He-rich (i.e. normal) PG 1159 stars, and the DO and DB white dwarfs. The two sequences are well defined by the time a central star is hot enough to ionize the nebula. We speculate that the parameter determining which sequence a proto-central star follows is the original metallicity, e.g. Fe abundance, of the star. Once on the H-rich sequence, there may be a crossing to a He-rich atmosphere due to extreme mass-loss (this might happen to the central star of He 2-131), but there is no evidence of changing back again.

7. References

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