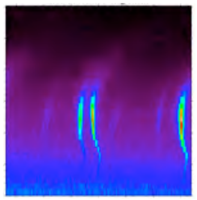
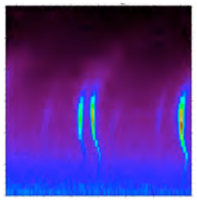


Asteroseismology:

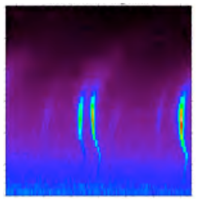
History and prescience

T.Appourchaux

Institut d'Astrophysique Spatiale

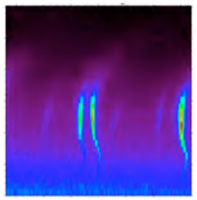


Drink wine !



History and prescience

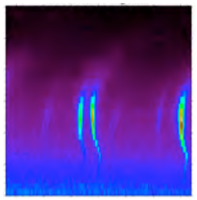
- Space asteroseismology
- Solar and stellar linewidths
- Solar g modes



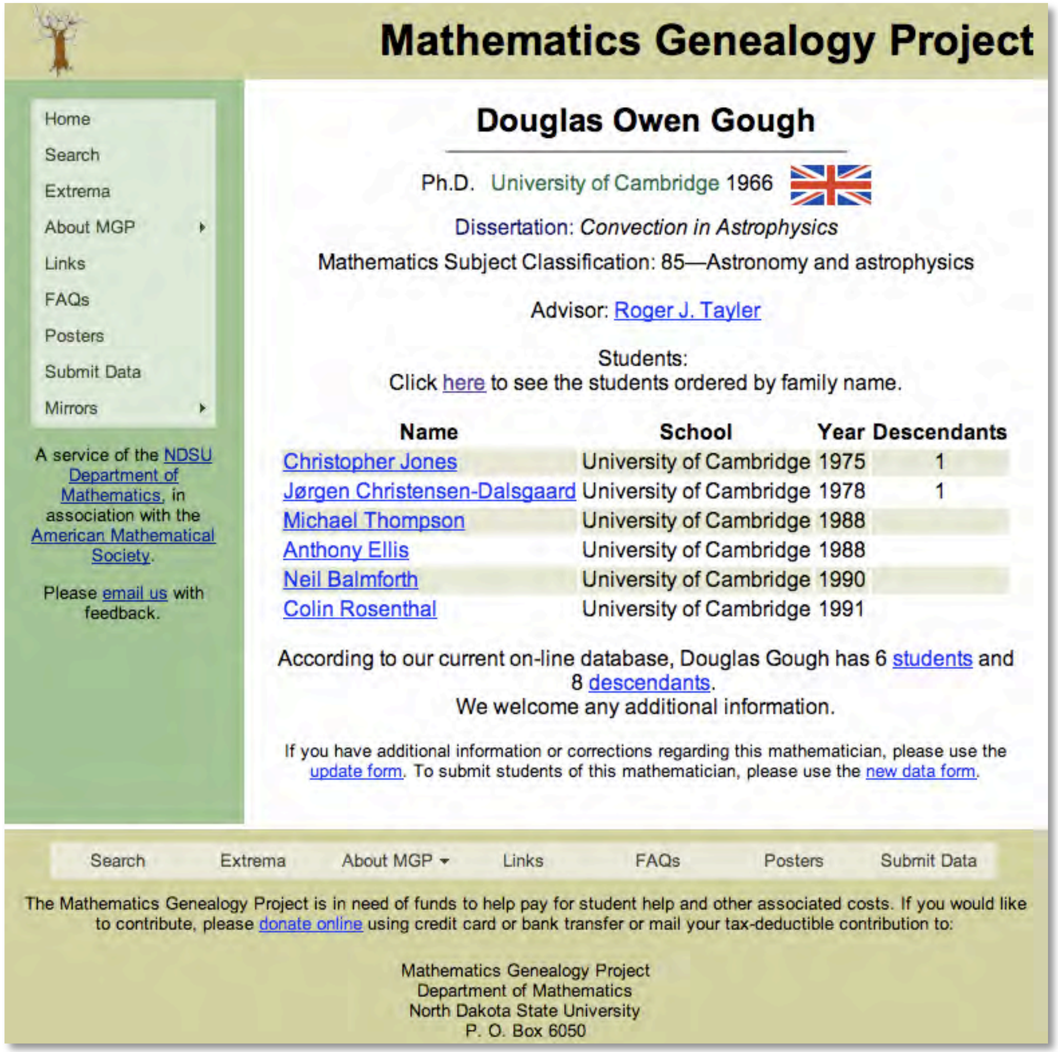
My regular point of view

In theory, there is no *difference* between theory and practice.

In practice there *is*.



The legacy of Douglas



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Please email us with feedback.

Douglas Owen Gough

Ph.D. University of Cambridge 1966

Dissertation: *Convection in Astrophysics*

Mathematics Subject Classification: 85—Astronomy and astrophysics

Advisor: Roger J. Tayler

Students:
Click here to see the students ordered by family name.

Name	School	Year	Descendants
Christopher Jones	University of Cambridge	1975	1
Jørgen Christensen-Dalsgaard	University of Cambridge	1978	1
Michael Thompson	University of Cambridge	1988	
Anthony Ellis	University of Cambridge	1988	
Neil Balmforth	University of Cambridge	1990	
Colin Rosenthal	University of Cambridge	1991	

According to our current on-line database, Douglas Gough has 6 students and 8 descendants.
We welcome any additional information.

If you have additional information or corrections regarding this mathematician, please use the update form. To submit students of this mathematician, please use the new data form.

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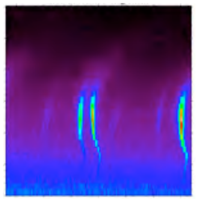
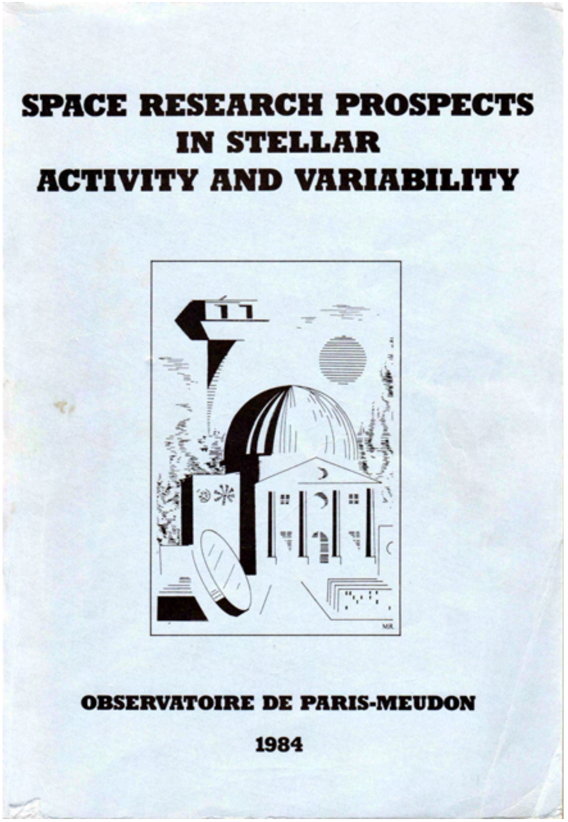
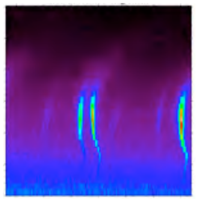


The birth of asteroseismology



Waves and Physics, Baia della Zaggare



JCD's seminal talk

WHAT WILL ASTEROSEISMOLOGY TEACH US?

Jørgen Christensen-Dalsgaard,

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK, and NORDITA,[1] Blegdamsvej 17, DK-2100 København Ø

Asteroseismology. [f. Gr. αστὴρ star + σεισμος shaking[2] +logy]. The science of using stellar oscillations for the study of the properties of stars, including their internal structure and dynamics. Cf. GEOSEISMOLOGY, HELIOSEISMOLOGY, SELENOSEISMOLOGY.

1 Introduction

Ever since stellar variability was first interpreted in terms of stellar oscillations, the periods have been used to gain information about the properties of the stars involved (e.g. Shapley 1914). Where only a single period is present this provides roughly a measure of the mean density of the star. The amount of information increases with the number of periods observed. In particular Petersen (1973) realized that for certain types of stars oscillating simultaneously in two different modes, the periods provide a fairly clean measure of the mass and radius of the stars. This technique has been applied extensively to double-mode

1. Present address.

2. e.g. Liddell & Scott (1940). The translation of σεισμος as earthquake (implied by the Oxford English Dictionary) appears to be ill-founded.

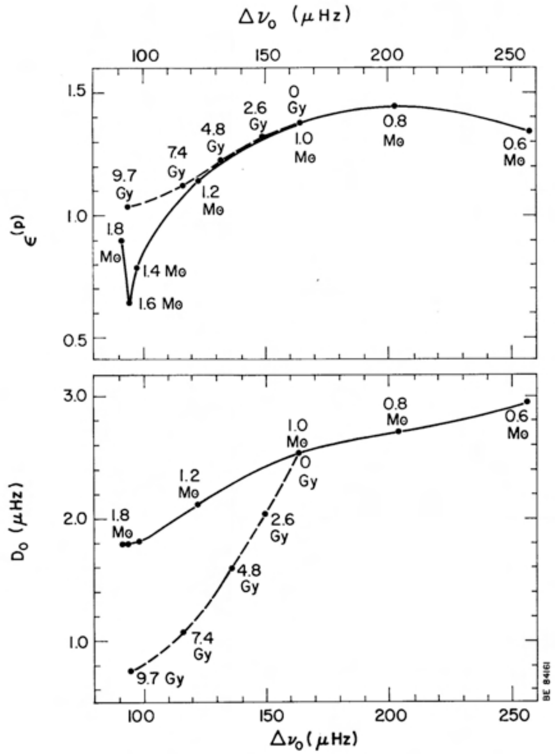
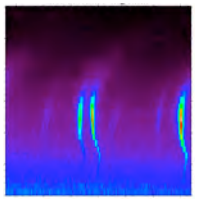


Figure 10. The location of the ZAMS (———) and of a 1 $M_\odot$ evolution sequence (– – – –) in $(\Delta\nu_0, \epsilon_0^{(p)})$ and $(\Delta\nu_0, D_0)$ diagrams. The positions of selected models have been indicated along the curves, labelled with masses (in $M_\odot$) or ages (in 10^9 years) of the models.

Christensen-Dalgaard (1984)



Lemaire's space mission

A STABILIZED PLATFORM CARRYING ONE OR TWO TELESCOPES

P. Lemaire
Laboratoire de Physique Stellaire et Planétaire
BP n° 10, 91370 Verrières le Buisson, France

I. INTRODUCTION

A space mission devoted to the study of stellar activity and variability has its own specific requirements in stability, spectral domains, accurate photometry and long term observations which cannot be fulfilled by an all purpose stellar mission. Such an all purpose stellar mission, e.g. IUE or ST, provides some insights into the sensitivity of chromospheric and transition line profiles to activity and, so, is appealing to a dedicated mission to study stellar activity.

From the ground, H and K CaII lines, formed in low chromospheres, provide the best activity index for late type stars, but the sensitivity threshold is limited by the disappearance of the emissive central core in hot stars. Space observatories give access to ultra violet lines being formed in high chromospheres and transition zones which are several times more sensitive to activity than the H and K CaII lines. The stellar activity is modulated by the star rotation and the record of data over several star rotations will give an important input on magnetic activity through the determination of active areas (the determination of activity cycles may be too ambitious for such a first mission).

The detection of stellar variability is a subject of controversy and a lot of inputs is given in this colloquium. As a preliminary conclusion, it seems that short period oscillations (up to fifteen minutes) can be detected and resolved with relatively high accuracy from the ground, at least for low magnitude and low rotator stars, by the mean of radial velocity measurement. From space, brightness fluctuation measurement with high photometric accuracy is accessible since the background noise introduced by atmospheric scintillation disappears and long series of continuous, uninterrupted, data can be recorded. So the theoretical

IV. WHITE LIGHT PHOTOMETRY AND SPECTROMETRY : TWO INSTRUMENTS

Decoupling on the same platform of the two complementary scientific objectives must lead to a better optimization of each instrument than with a unique system.

a White light photometry

The photometric system is an assembly of several, wide field, compact light collectors oriented in several directions in order to record simultaneously bright stars in the sky. Each collector may use a wide field lens and a PIN diode array detector. A 30 cm diameter lens collects more thant 10^7 photons/sec on a V = 4 star and a continuous observational sequence of 60 days is able to get a 0.1 micromagnitude resolution.

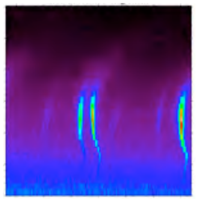
This scheme, proposed by G. Isaak, is very attractive to optimize the observing time in getting long records of brigthness fluctuations on several stars at the same time. Up to now no evaluation has been made to know the precise characteristics of the instrumental mounting and the performances (signal to noise ratio, field of view...).

b Spectroscopy

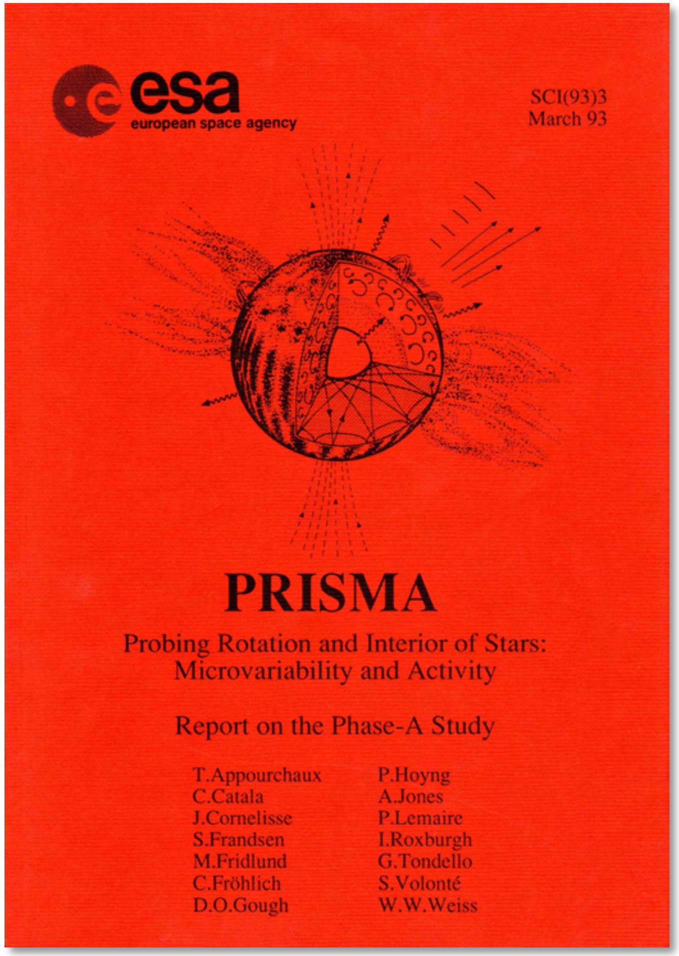
As seen earlier the photometry requires long records on the same target, so it is necessary to optimize the spectrographic system to analyze the activity of several stars during these observations. The instrumental scheme for activity must include a system with enough field to have the opportunity to get several stars and also a system with its own field selector to periodically scan several fields (which contain the photometric stars).

A coelostat (plane mirror) selects the field of view of the light beam focused by an off-axis paraboloïd (Figure III). The entrance slot of the spectrograph limits the field of view. Then an off-axis paraboloïd collimates the beam on a plane grating and the diffracted

Lemaire (1984)



PRISMA Science



esa
european space agency

SCI(93)3
March 93

PRISMA

Probing Rotation and Interior of Stars: Microvariability and Activity

Report on the Phase-A Study

T.Appourchaux, C.Catala, J.Cornelisse, S.Frandsen, M.Fridlund, C.Fröhlich, D.O.Gough, P.Hoyng, A.Jones, P.Lemaire, I.Roxburgh, G.Tondello, S.Volonté, W.W.Weiss

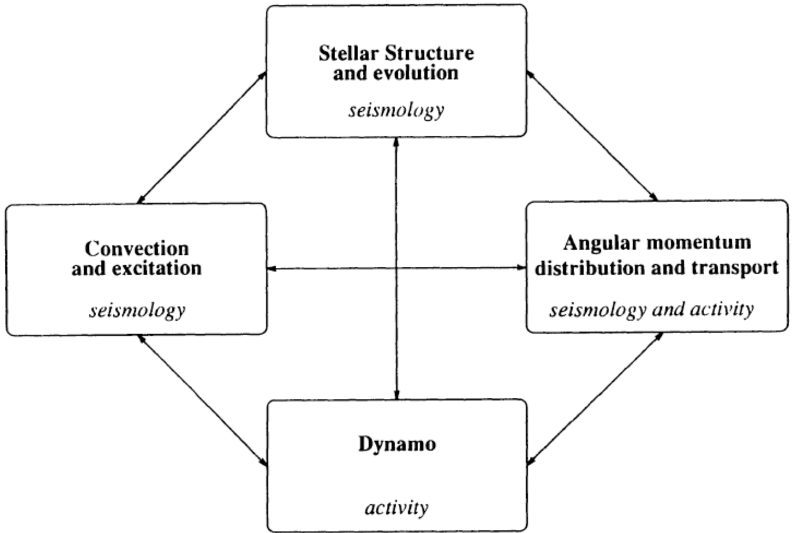
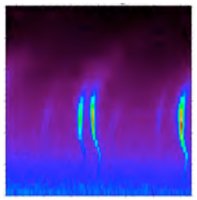


FIGURE II.

Appourchaux et al (1992)

Observables	Range	Accuracy	Scientific keywords
Frequencies	0.02 mHz-0.1 Hz	0.1 μHz	Stellar structure, g modes, He content, neutrino physics
Amplitudes	10^{-6}-10^{-1}	10^{-7}-10^{-5}	Excitation, stellar spots and plages, non-linear pulsators?, convection
Linewidths	1-10 μHz	0.05 μHz	Excitation, convection, surface structure
Frequency separations	>0.3 μHz	0.1 μHz	Stellar parameters, stellar structure, rotation, magnetic fields

Appourchaux et al (1993)



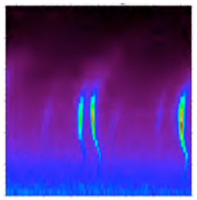
PRISMA targets

A better test of stellar structure models can be achieved if one or several basic stellar parameters are known independently. This is why a very high priority must be given to possible targets for which independent information is available, or for which additional constraints can be placed on the models:

- Members of open clusters, for which a good estimate of the age is available.
- Members of some binary systems, for which the masses, and sometimes the radii, are well known.
- Stars observed by HIPPARCOS, for which we have a good determination of the absolute luminosity.
- Stars observed by IUE and ROSAT
- Stars observed in the Mount Wilson CaII program

Besides these prime targets which will drive the instrument and strategy definition, the scientific return of the mission will be maximized if a sample of very important targets are included: these are the classical pulsating variables, such as δ Scuti, RR Lyrae, Cepheids, λ Boötis, and also rapidly oscillating Ap stars, Am stars and Maia variables. These targets should not drive the major requirements of the mission, but the philosophy would be to observe them with PRISMA whenever possible.

Appourchaux et al (1993)



How many stars in a cluster ?

For 15 orders

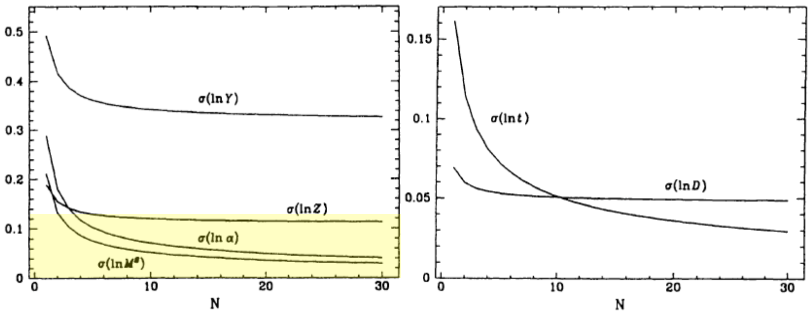


FIGURE V. Standard errors $\sigma(\alpha_i^s)$ associated with inferred stellar parameters α_i^s in a cluster of N stars, assuming observational errors $\delta\beta_{\mathrm{obs},k}^s$ with standard errors $\sigma(\ln T_e^s) = 0.01$, $\sigma(\ln m_v^s) = 0.01$, $\sigma(\ln g^s) = 0.1$, $\sigma(\Delta^s) = 0.05\mu$Hz, $\sigma(d^s) = 0.7\mu$Hz, $\sigma(\ln(Z/X)) = 0.1$, $\sigma(\ln D) = 0.1$. The seismic parameters Δ^s and d^s are presumed to have been obtained from frequencies of modes having standard errors 1 μHz and with $14 \leq n+l/2 \leq 28$ and $0 \leq l \leq 2$, only half of which are measured.

For 23 orders

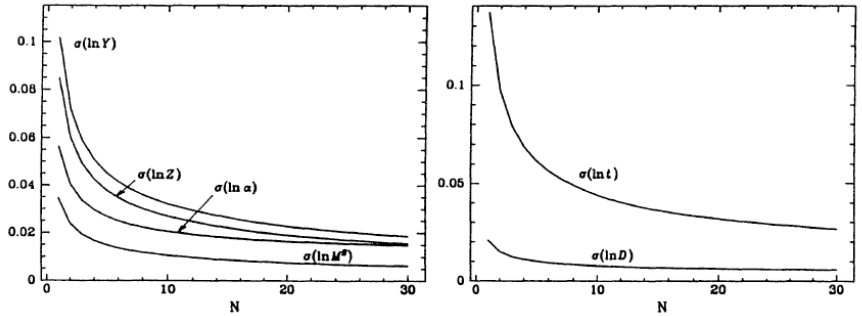
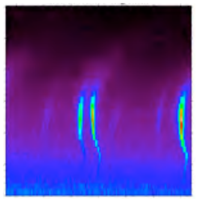


FIGURE VI. Standard errors in a stellar cluster calibration similar to that illustrated in Figure V, but whose data have been supplemented with additional values of Δ^s and d^s, obtained this time from modes with $6 \leq n + l/2 \leq 28$ and $0 \leq l \leq 2$, though with the same standard errors as those associated with the original data, namely 0.05 μHz and 0.7 μHz respectively.

Still key today !

Appourchaux et al (1992)
Gough and Novotny (1993)



Then STARS, Eddington...

STARS

GONG'94: Helio- and Astero-Seismology
ASP Conference Series, Vol. 76, 1995
R.K. Ulrich, E.J. Rhodes, Jr. and W. Däppen (eds.)

STARS: A PROPOSAL FOR A DEDICATED SPACE MISSION TO STUDY STELLAR STRUCTURE AND EVOLUTION

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K. SCHRIJVER
Lockheed - Palo Alto Research Laboratories, Palo Alto, California, USA

ABSTRACT STARS is an asteroseismological space mission, currently under Phase-A Study by the European Space Agency (ESA) as a candidate for the M3 mission. This report summarizes the conclusions of the Assessment Study; it is based on presentations made in Paris early in May 1994 to the ESA selection committees and to interested members of the scientific community.

INTRODUCTION

STARS is a mission aimed at providing an empirical framework to gain new insight into the physics of stellar evolution, and into the connexion between the interiors and the visible surfaces of stars. The mission will address basic stellar structure. It will enable us to investigate the physics of stellar interiors: for example, the equation of state, the opacity of stellar material, and energy and angular momentum transport by convection and by waves. These are all areas in which greater knowledge is required to build a really reliable theory of stellar

416

Fridlund et al (1995)

Eddington

BACKGROUND TO THE *EDDINGTON* MISSION

I. W. Roxburgh[1,2]

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ABSTRACT

The *Eddington* mission to measure stellar oscillations and search for other planets builds on a solid history of earlier proposals and studies for space missions to study stellar seismology and stellar activity and to search for planets. The idea of such a mission for stellar activity and seismology was conceived in France 1981 and underwent a series of developments leading to the EVRIS mission which was a passenger experiment on Mars96 and was lost when Mars96 failed. Subsequent proposals PRISMA and STARS underwent Phase A studies in ESA but were not selected for launch. The small French mission COROT, originally conceived as a successor to EVRIS was selected by CNES and is now scheduled for launch in 2004. The much more ambitious *Eddington* mission, devoted to stellar seismology and planet searching was selected as a mission (albeit with a "reserve" status) in the 2000 F2/F3 selection round in ESA. The mission is proceeding with detailed industrial and working group studies with the aim of being ready for launch in 2007/8 should the mission be fully approved as part of the ESA programme.

Key words: waves – missions: *Eddington* – stars: oscillations – planets: search

1. THE BIRTH OF EVRIS

The idea of a small space mission dedicated to stellar activity was first conceived on 10th May 1981 (the day Mitterand was first elected President of France), at an informal workshop on solar and stellar activity organised by André Mangeney in Corrèze. During the discussions on rotational modulation of stars the idea emerged to have a satellite devoted to observing the evolution in time of stellar activity indicators in a range of wavelengths. Thus the concept of satellite project was born. Among the participants were André Mangeney, Françoise Praderie and Philip Lemaire who led the drive to get such a space mission in the following years.

Later that summer at a small workshop in Paris to discuss the proposed space mission Annie Baglin and Philip Delache proposed extending the mission to include stellar micro-oscillations; this concept was first presented at a Séminaire de Prospective du CNES at Les Arcs in September 1981.

In April of the following year (1982) the first proposal was submitted to CNES by Mangeney, Baglin, Le Contel, Lemaire, Praderie and Vauclair, (Mangeney et al. 1982a), with the title *Projet de mission spatiale pour l'étude de la variabilité et de l'activité des étoiles: EVRIS (Etude de la Variabilité, de la Rotation et des Intéreieurs Stellaires).* This led to a phase 0 study at CNES on the possibility of such a mission. In the following two years several attempts were made to get the proposed EVRIS mission funded and a proposal for CNES support to start laboratory experiments on photomultipliers and to support students was successful and continued for several years (Mangeney et al. 1983). In the search for implementation of EVRIS the same mission concept – now renamed as PSIVA – was presented to ESA's Astronomy Working Group and proposed to NASA as a possible experiment on the Space Station, but these were not successful (Mangeney et al. 1982b).

2. THE INTERNATIONAL MISSION PRISMA

During the first few years the drive for such a space mission came entirely from French scientists, although several colleagues (including the author) expressed interest in the project and where possible gave it support. The wider community was brought into the project through an International Workshop in Meudon on "Space Research Prospects in Stellar Activity and Variability"; several of us in this *Eddington* meeting were present at that Meudon meeting which sowed the seeds for future international cooperation. The proceedings, edited by Praderie and Mangeney (1984), are well worth reading to get an understanding of what people thought and dreamt about at that time!

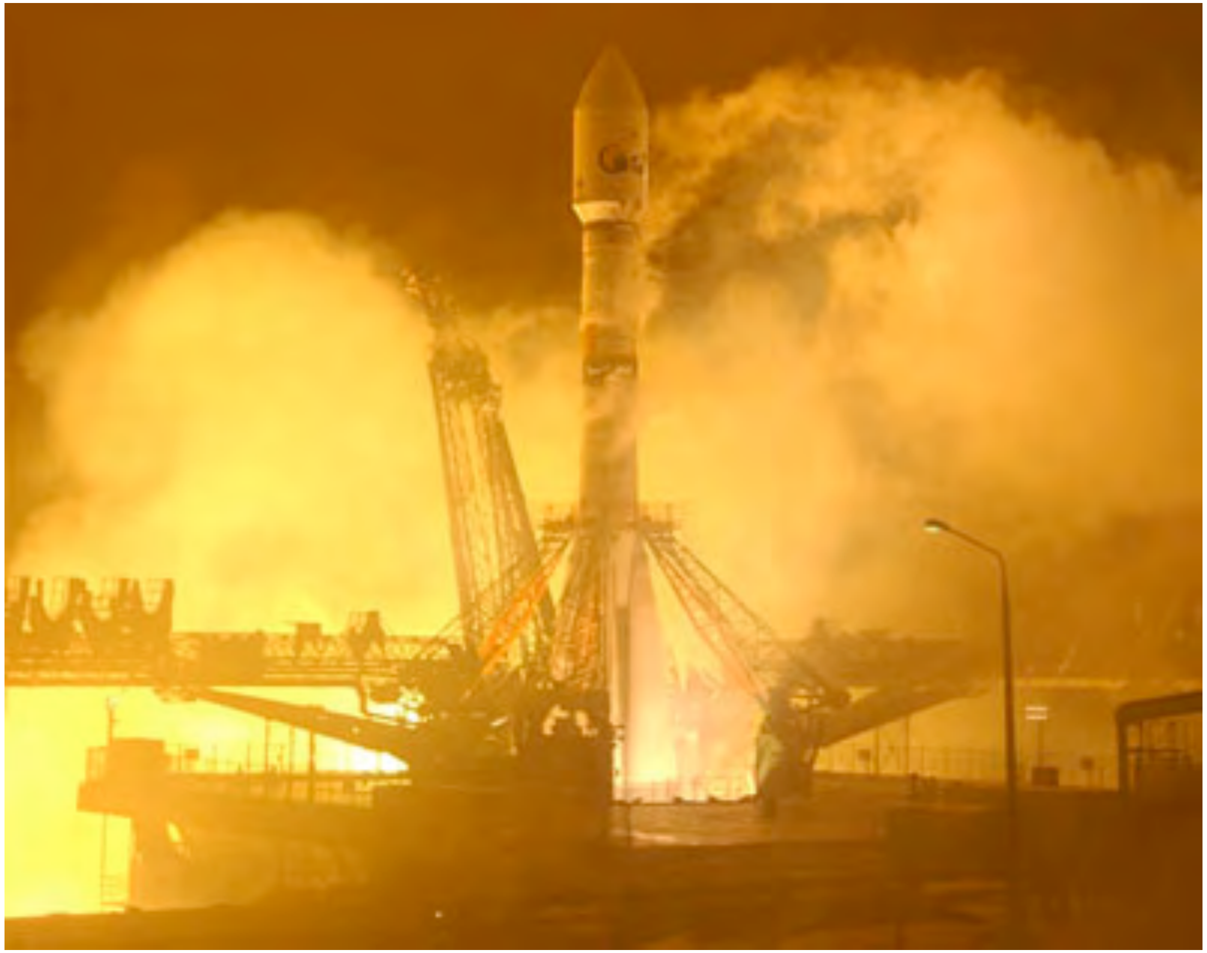
At the same time ESA was thinking through its future programme under the leadership of Roger Bonnet recently appointed as the new Director of Science. Bonnet set up a Horizon 2000 Survey Committee to produce a future plan for the Agency's science programme. In response to a call for ideas the EVRIS concept relabelled as PSAPISA "Probing Stellar and Planetary Interiors via Seismology and Activity" was proposed as a possible experiment on a modified Eureca platform.

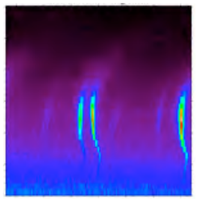
I was fortunate enough to be appointed to the Horizon 2000 Astronomy Survey Panel (primarily to cover fundamental physics) but I was therefore in a position to stress

Proc. 1st *Eddington* workshop *"Stellar Structure and Habitable Planet Finding"*, Córdoba, 11–15 June 2001 (ESA SP-485, January 2002, F. Favata, I. W. Roxburgh & D. Galadí-Enríquez eds.)

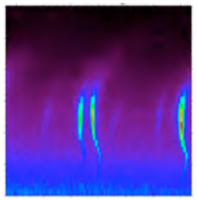
Roxburgh (2002)

CoRoT mission (End 2006)



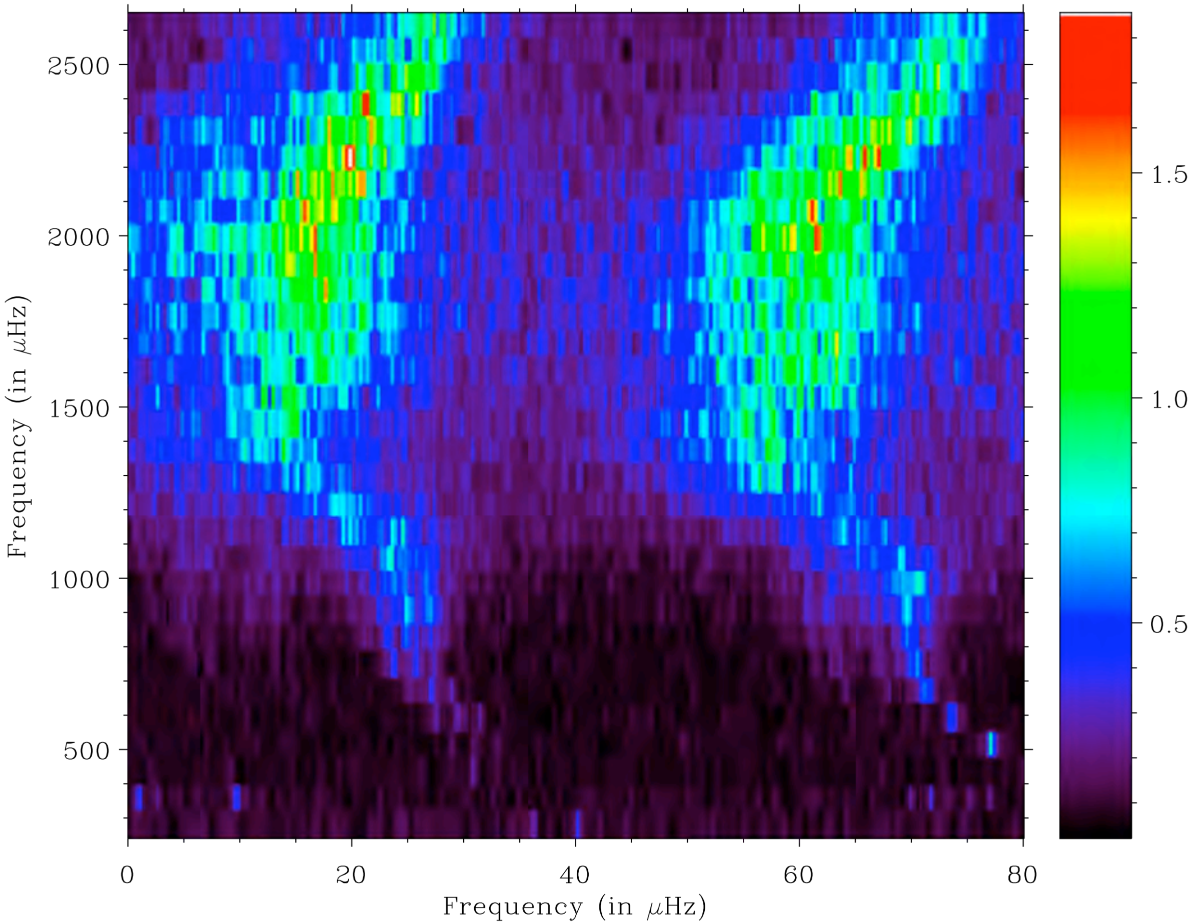


A few results for single stars
from
current space missions

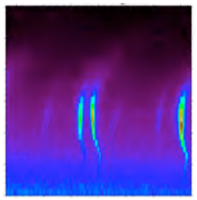


HD49333 Echelle diagramme

Before CoRoT launch

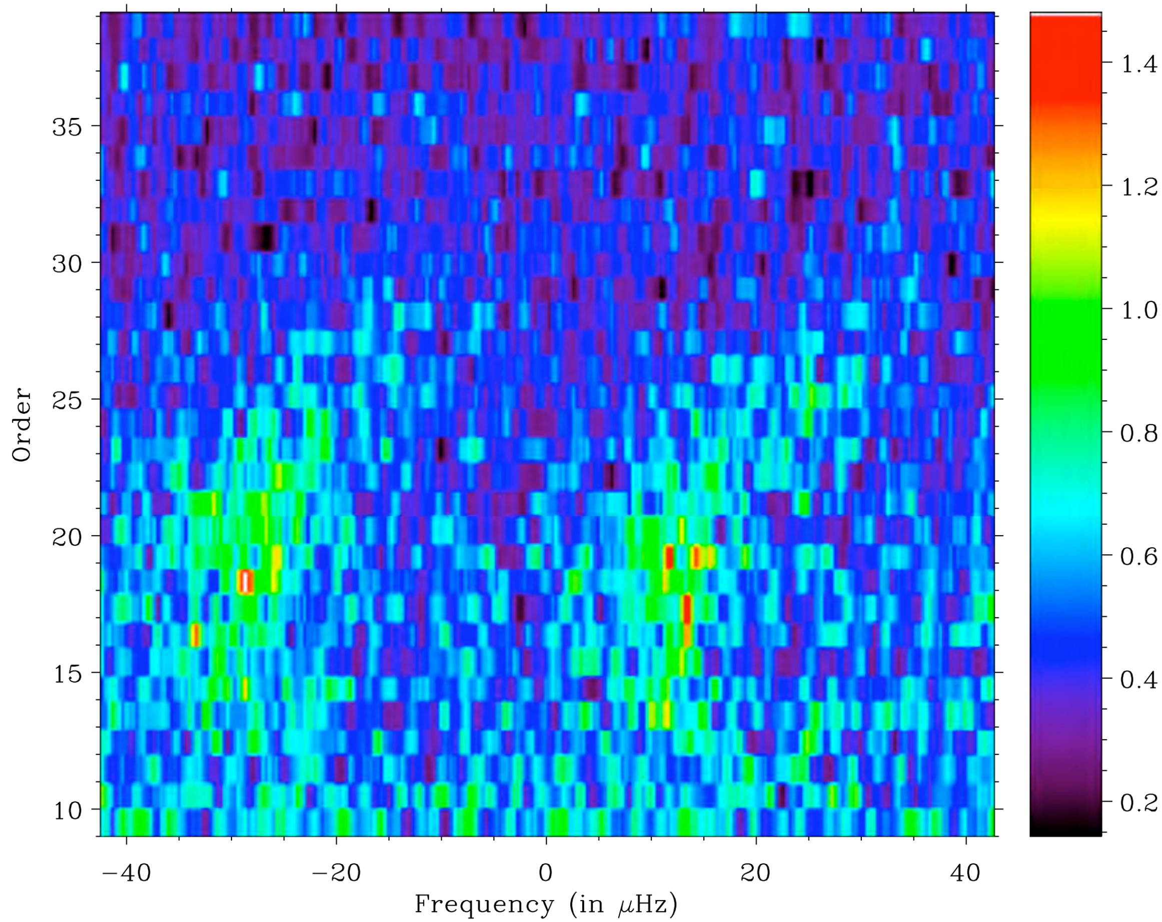


Appourchaux et al (2006)

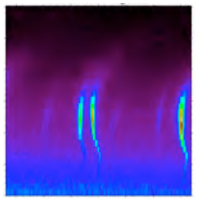


HD49333 Echelle diagramme

After CoRoT launch



Appourchaux et al (2008)



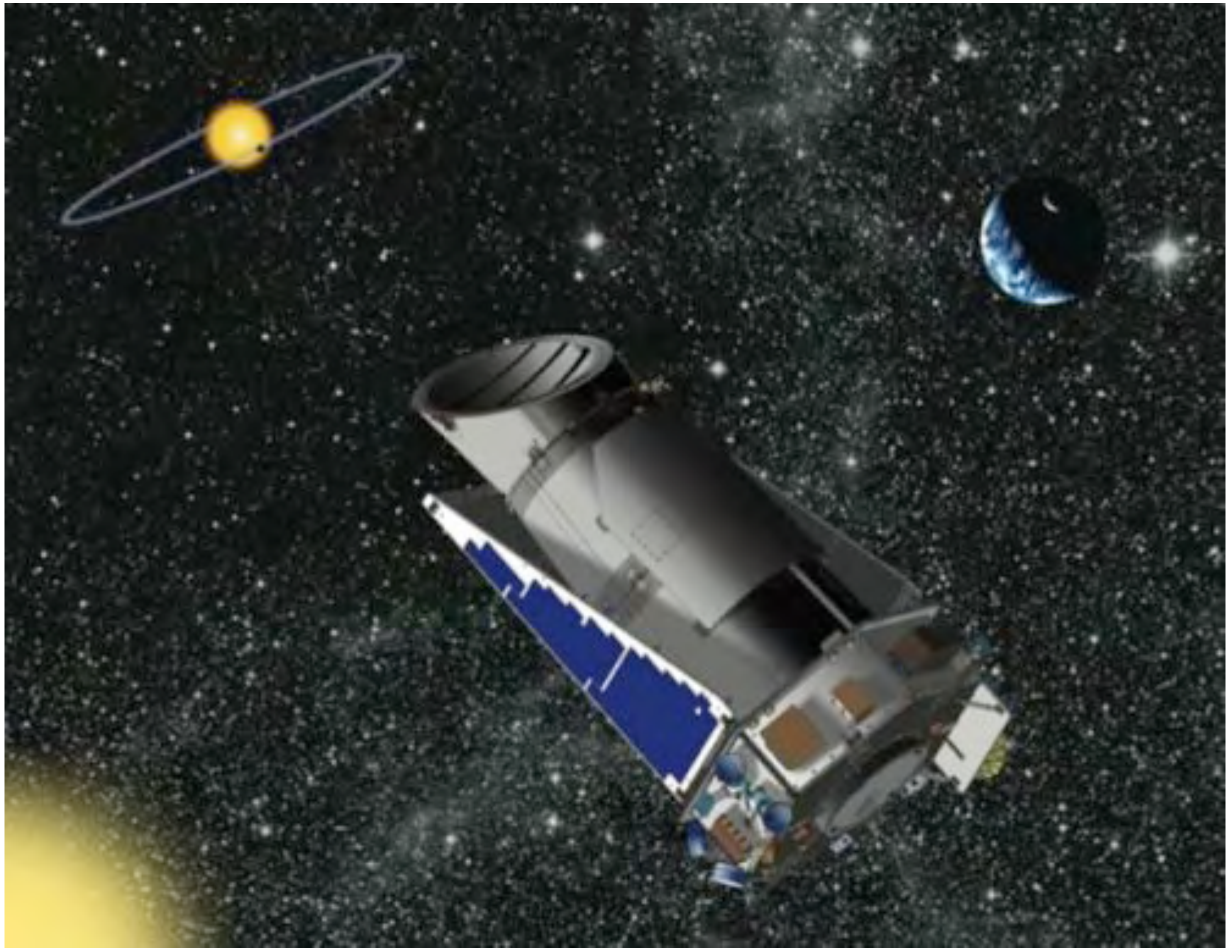
Solving of HD49333 syndrome

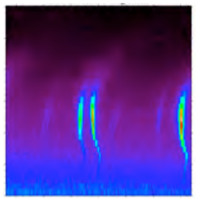
- Use of a Bayesian approach based on mode amplitude ratio (Appourchaux et al, 2008; Benomar et al, 2009a,b; Gruberbauer et al, 2009; Campante and Handberg, 2011)
- Use of ε vs Effective temperature (White et al, 2011)
- Use of homologous scaling of the asymptotic relation (Bedding and Kjeldsen, 2010; Jarvis et al, 2012)

Use of theoretical prejudices in all cases...

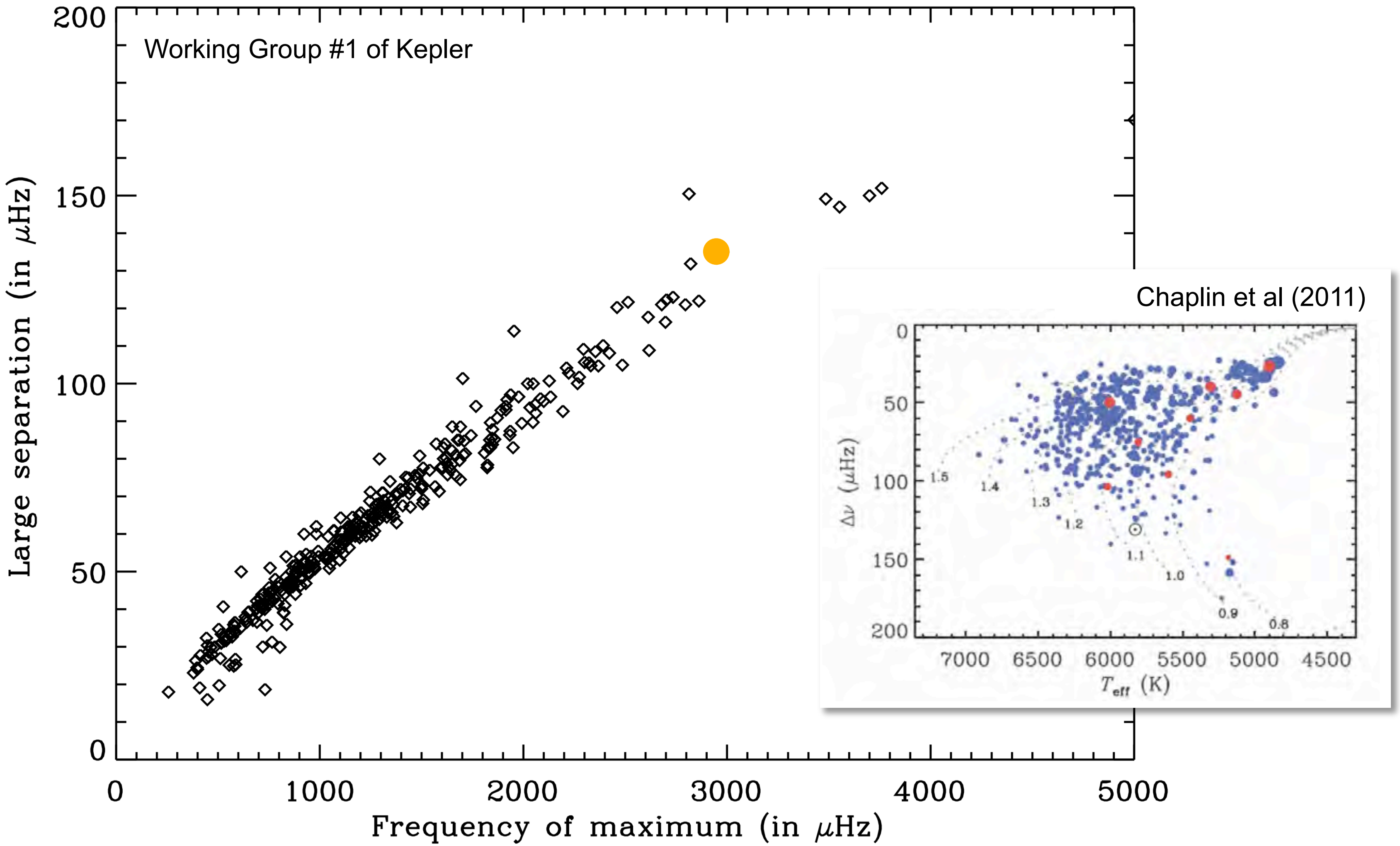
We are all Bayesian !

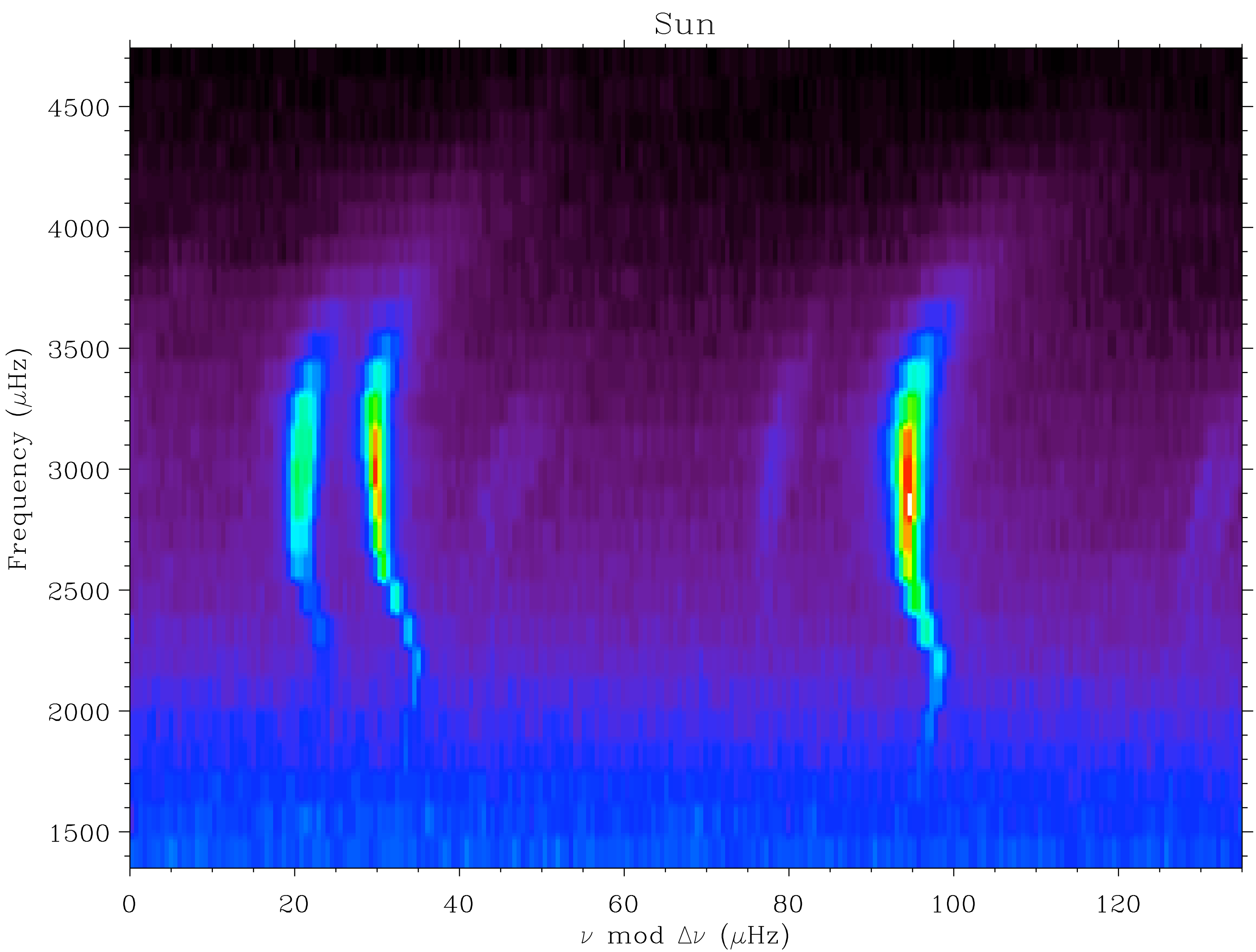
Kepler mission (Beg. 2009)



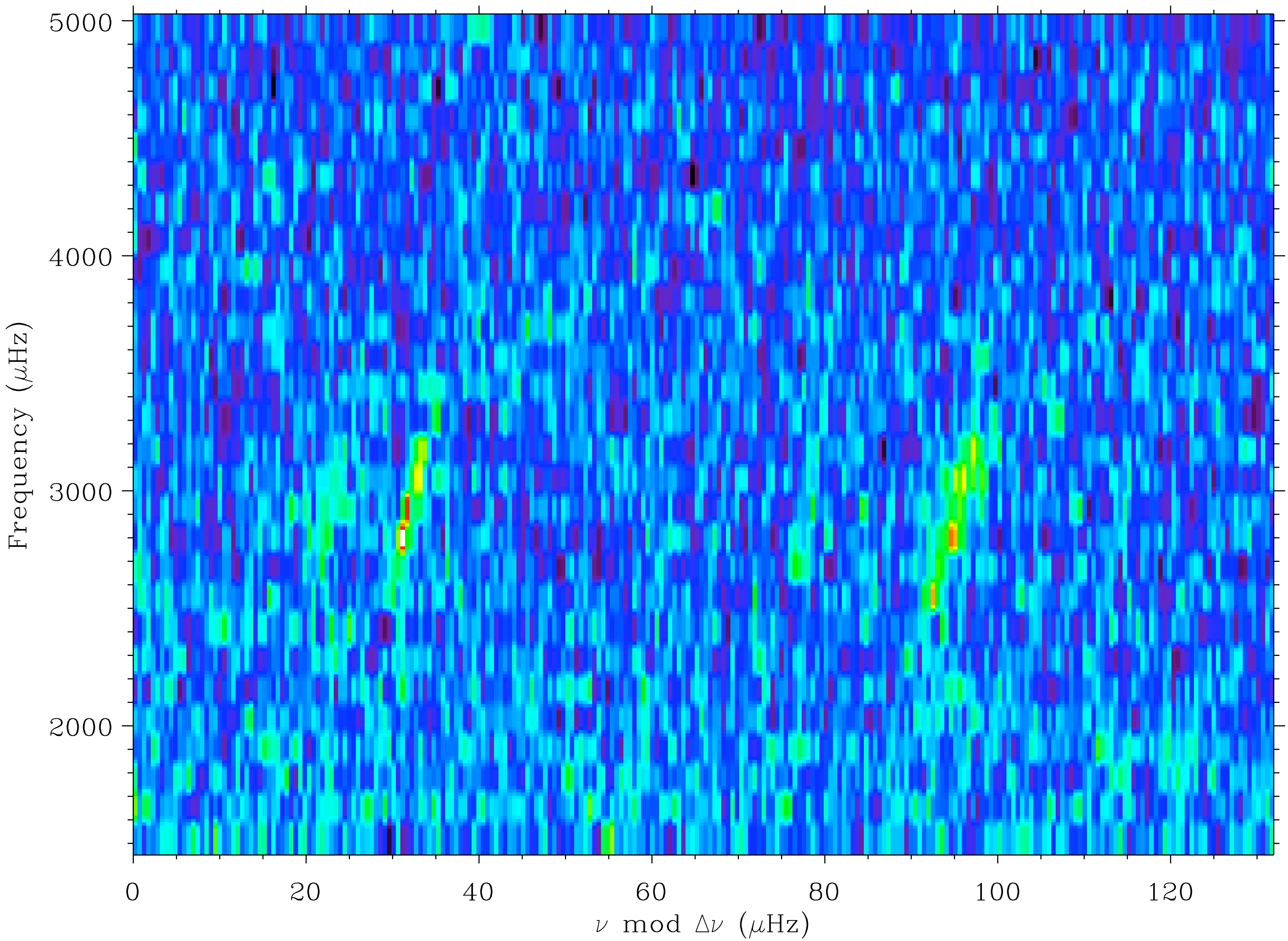


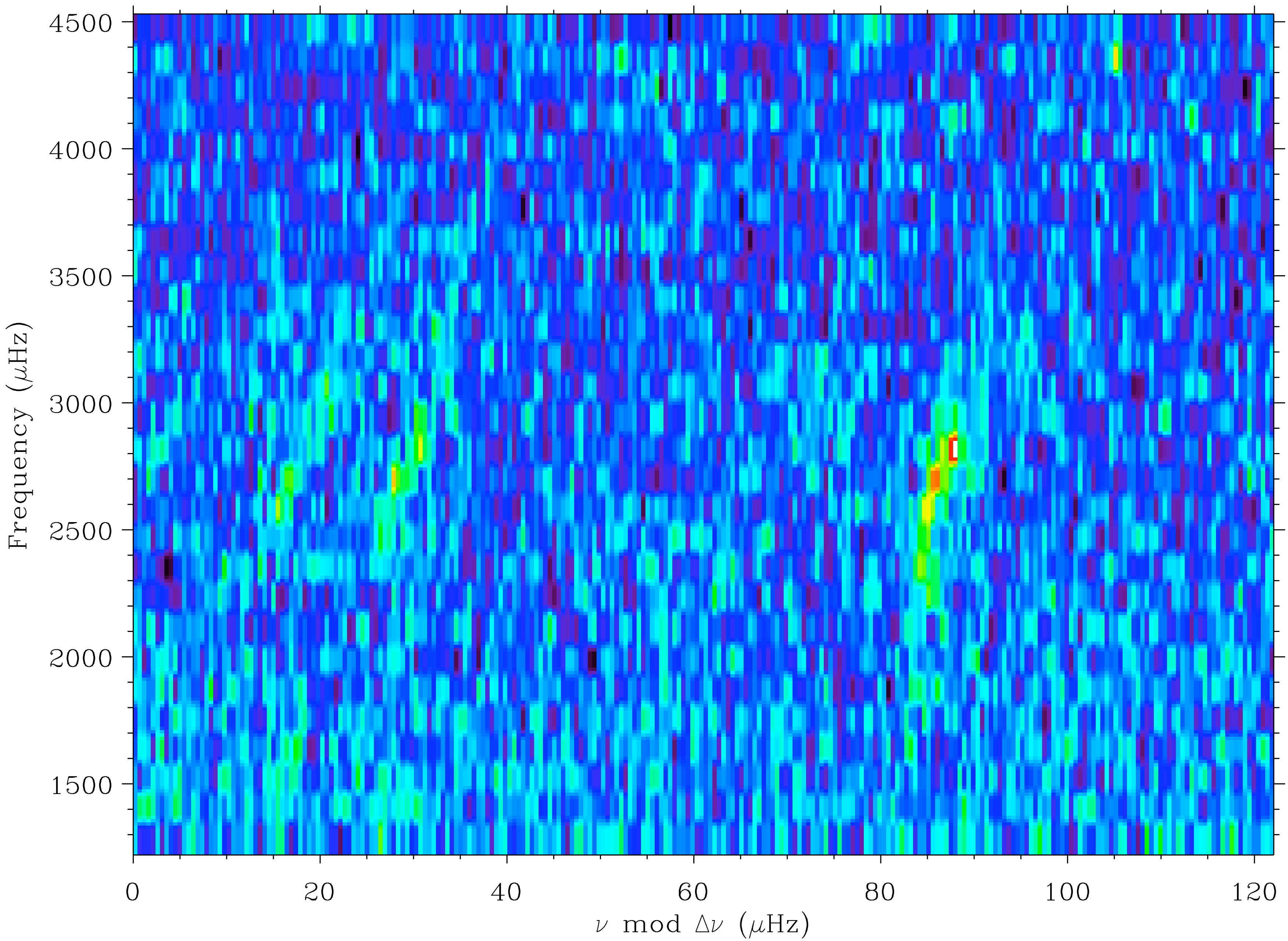
An orchestra of stars





Sun
Frequency (μHz)
4500
4000
3500
3000
2500
2000
1500
0
20
40
60
80
100
120
ν mod Δν (μHz)


5000
4000
3000
2000
Frequency (μHz)
0
20
40
60
80
100
120
ν mod Δν (μHz)



4500
4000
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Frequency (μHz)
0
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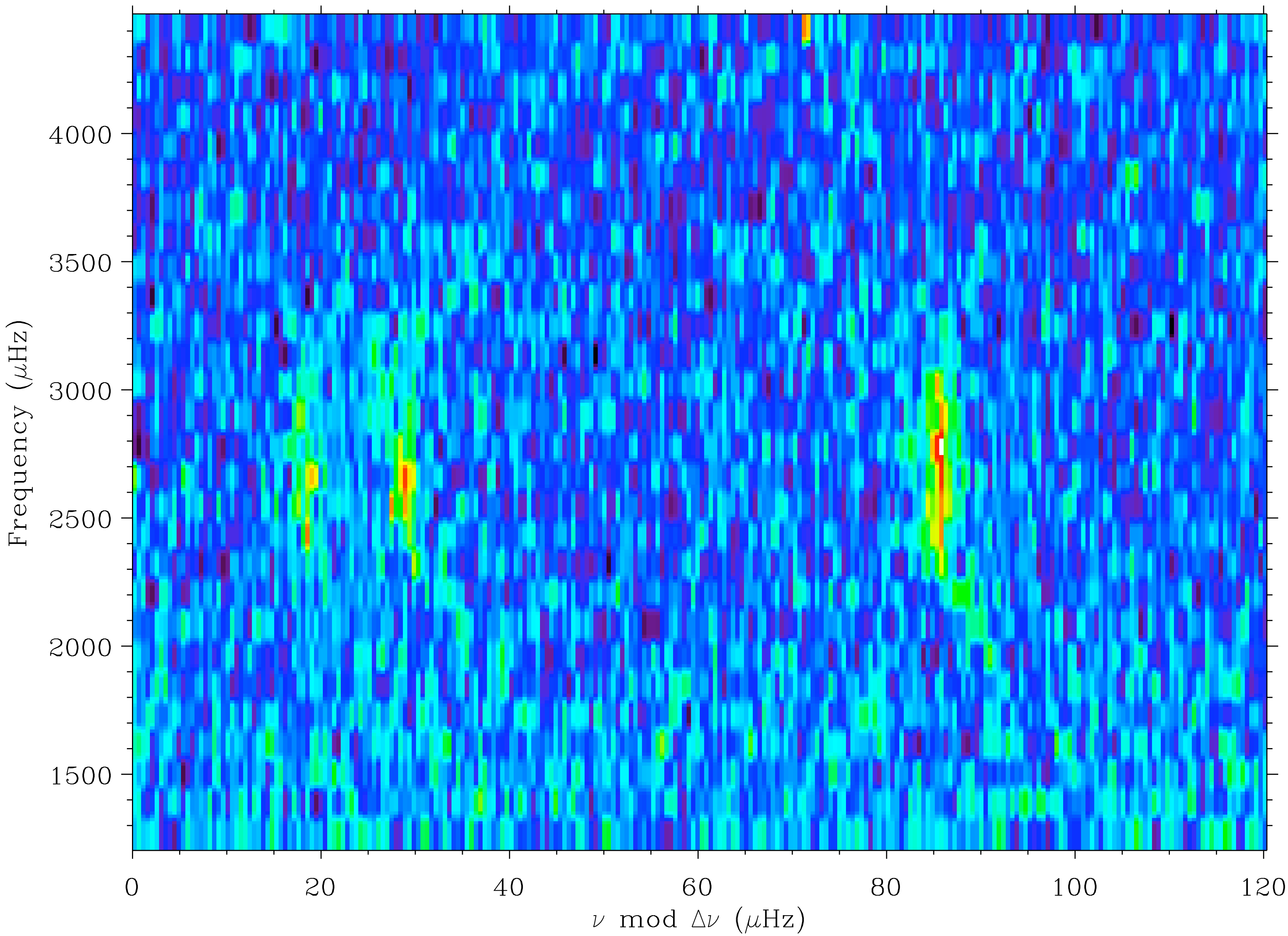
ν mod Δν (μHz)



Frequency (μHz)
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3000
3500
4000
0
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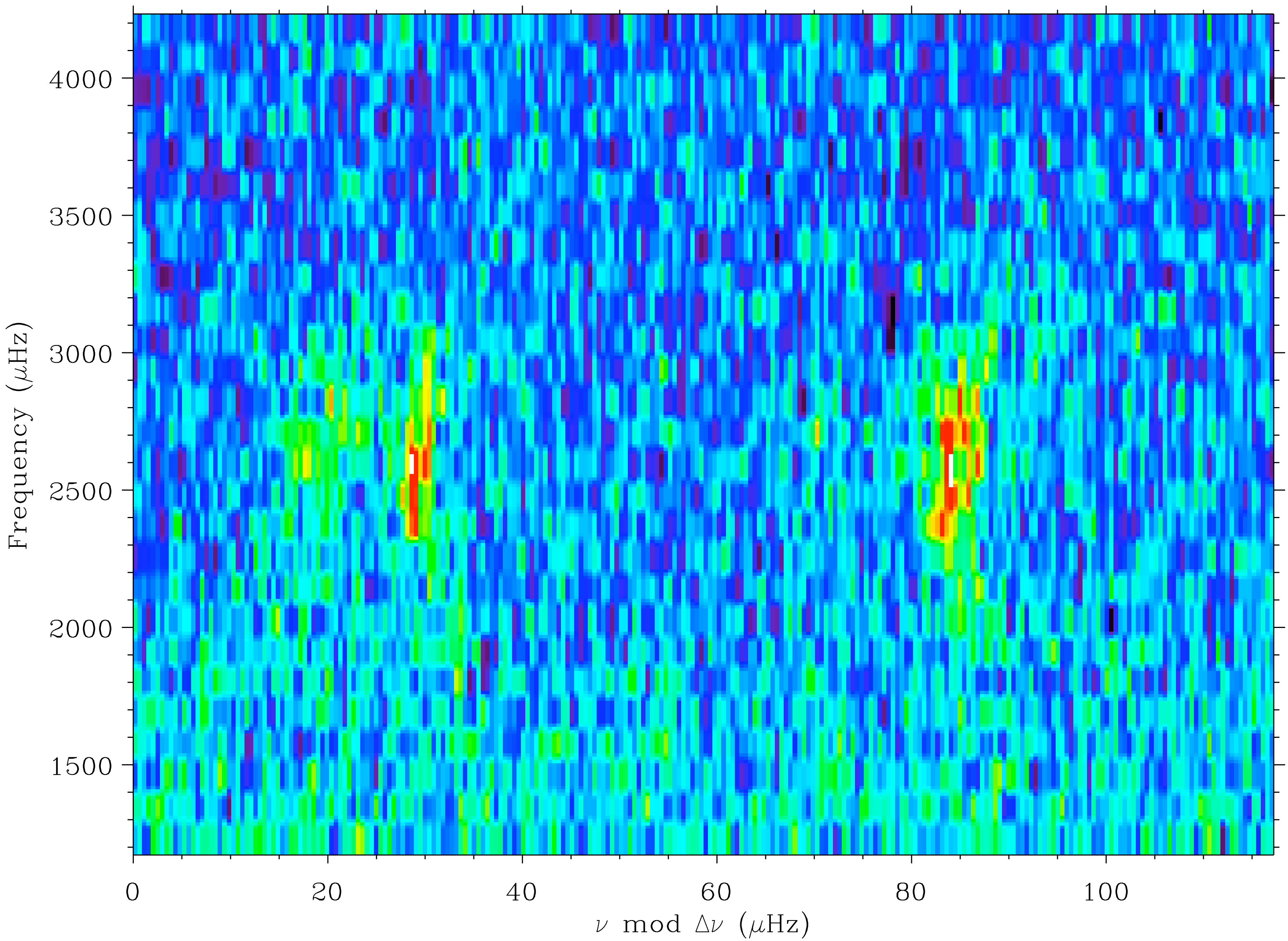
40
60
80
100
120
ν mod Δν (μHz)



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Frequency (μHz)
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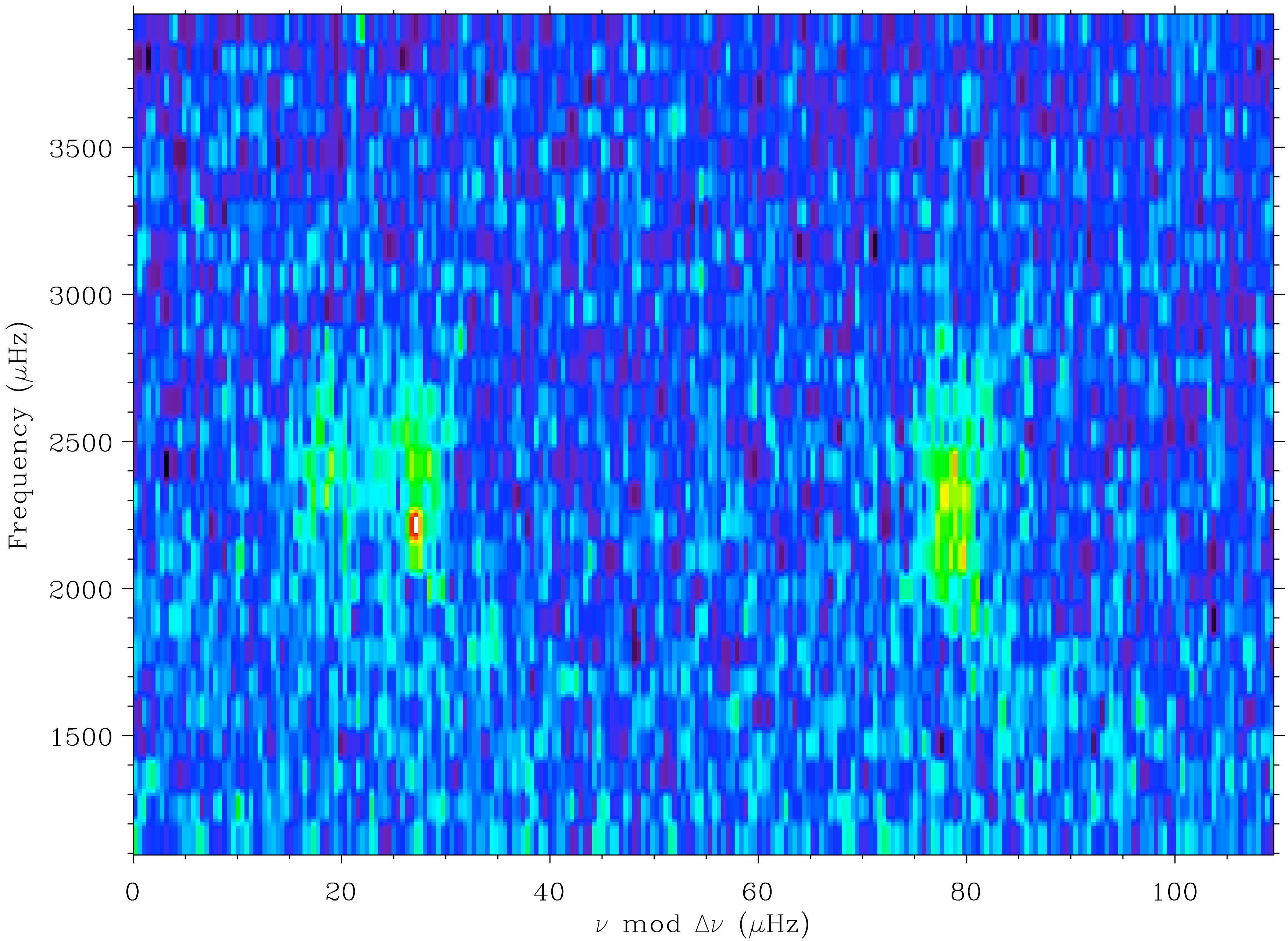
20
40
60
80
100
ν mod Δν (μHz)



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Frequency (μHz)
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20
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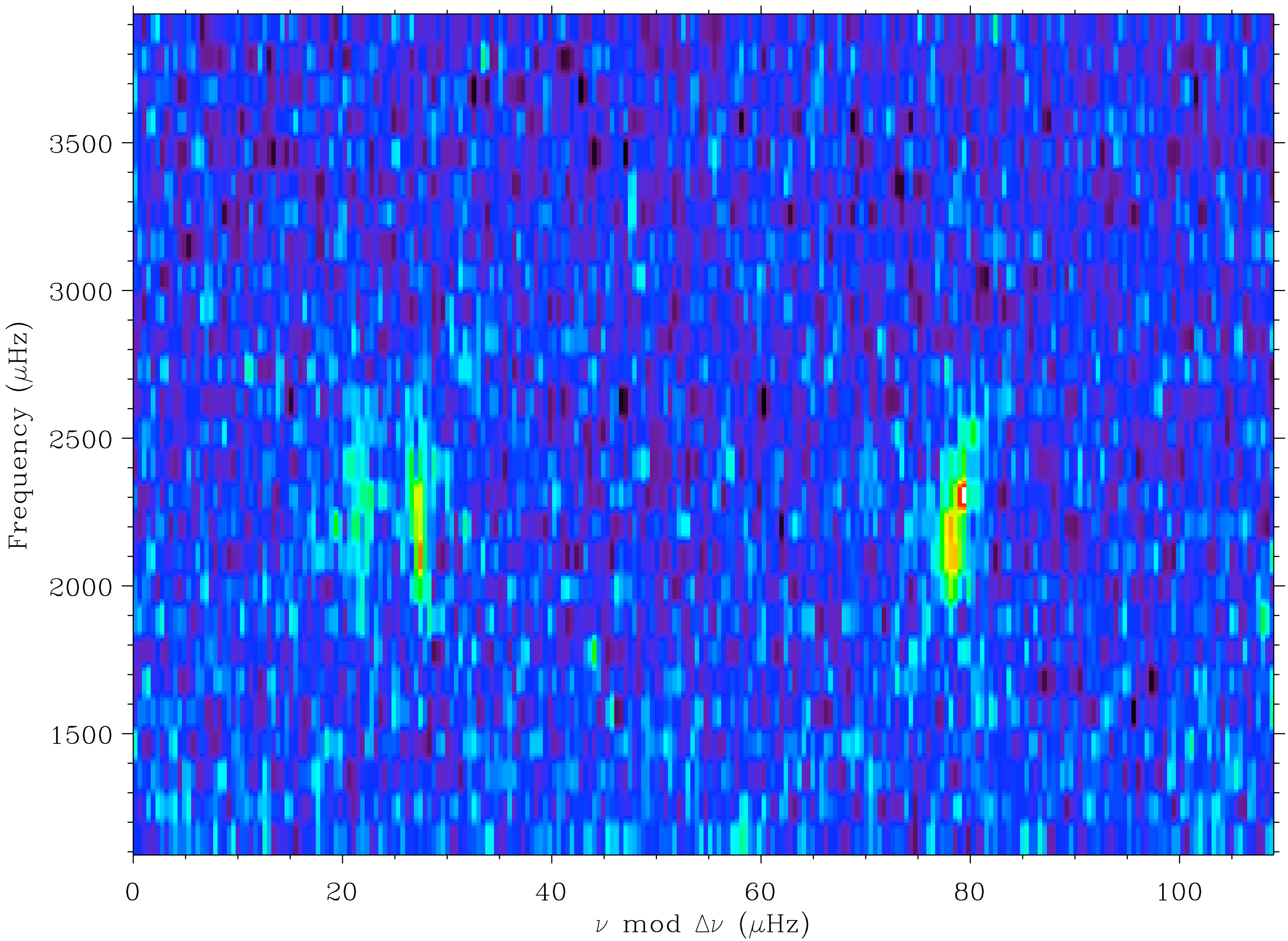
60
80
100
ν mod Δν (μHz)



Frequency (μHz)
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1500
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20
40
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80
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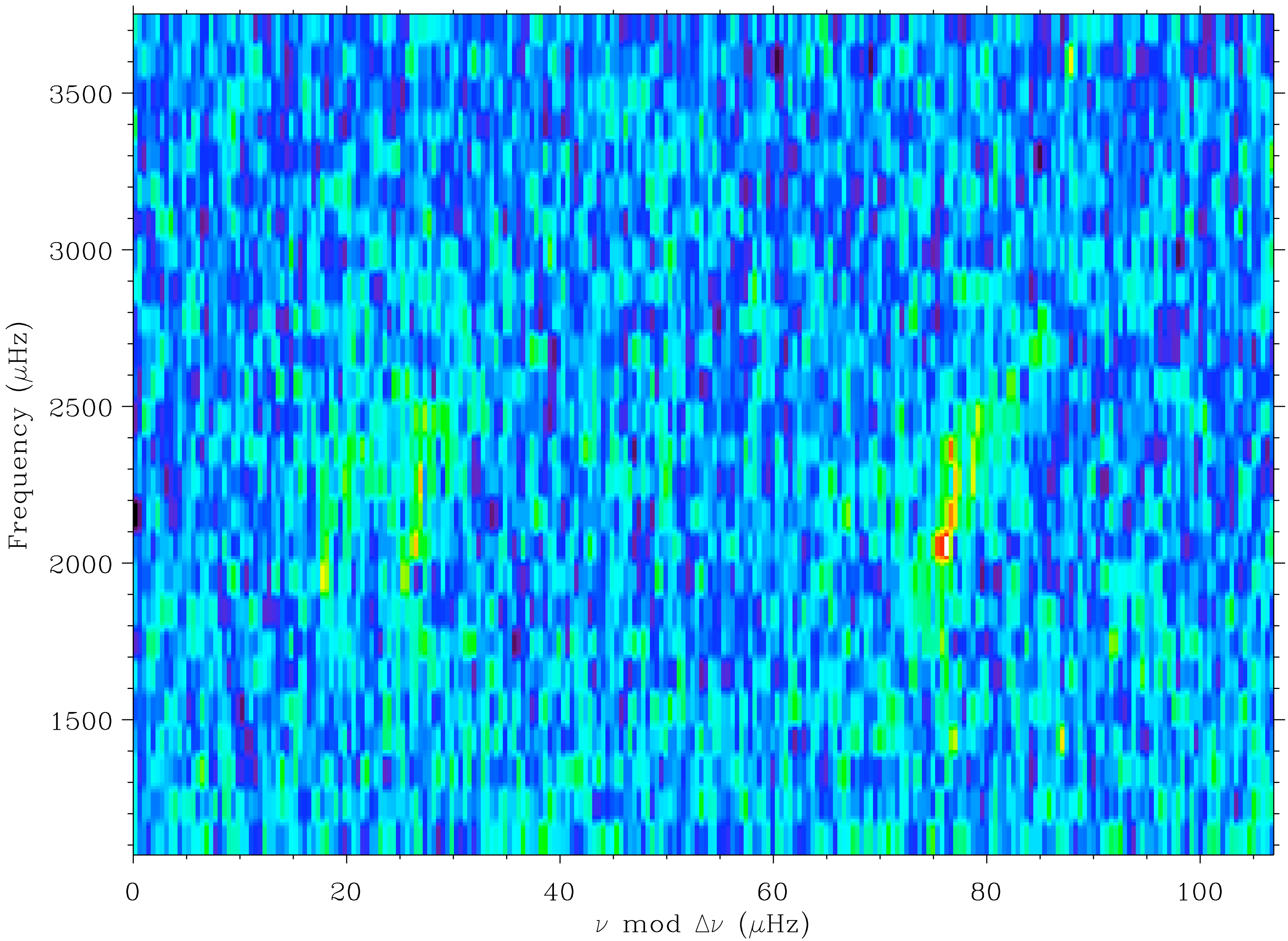
ν mod Δν (μHz)



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3000
2500
2000
1500
Frequency (μHz)
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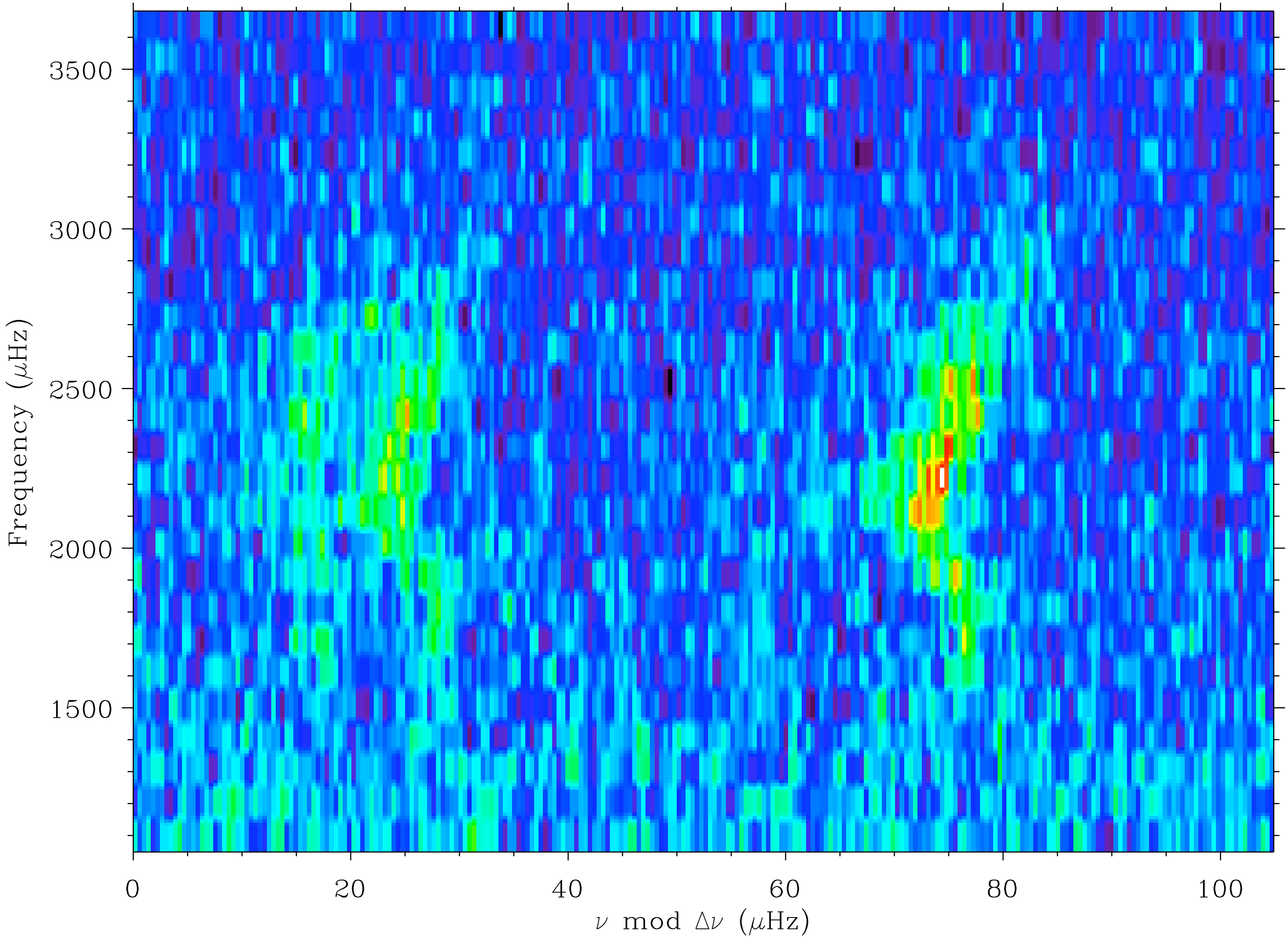
20
40
60
80
100
ν mod Δν (μHz)



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3000
2500
2000
1500
Frequency (μHz)
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40
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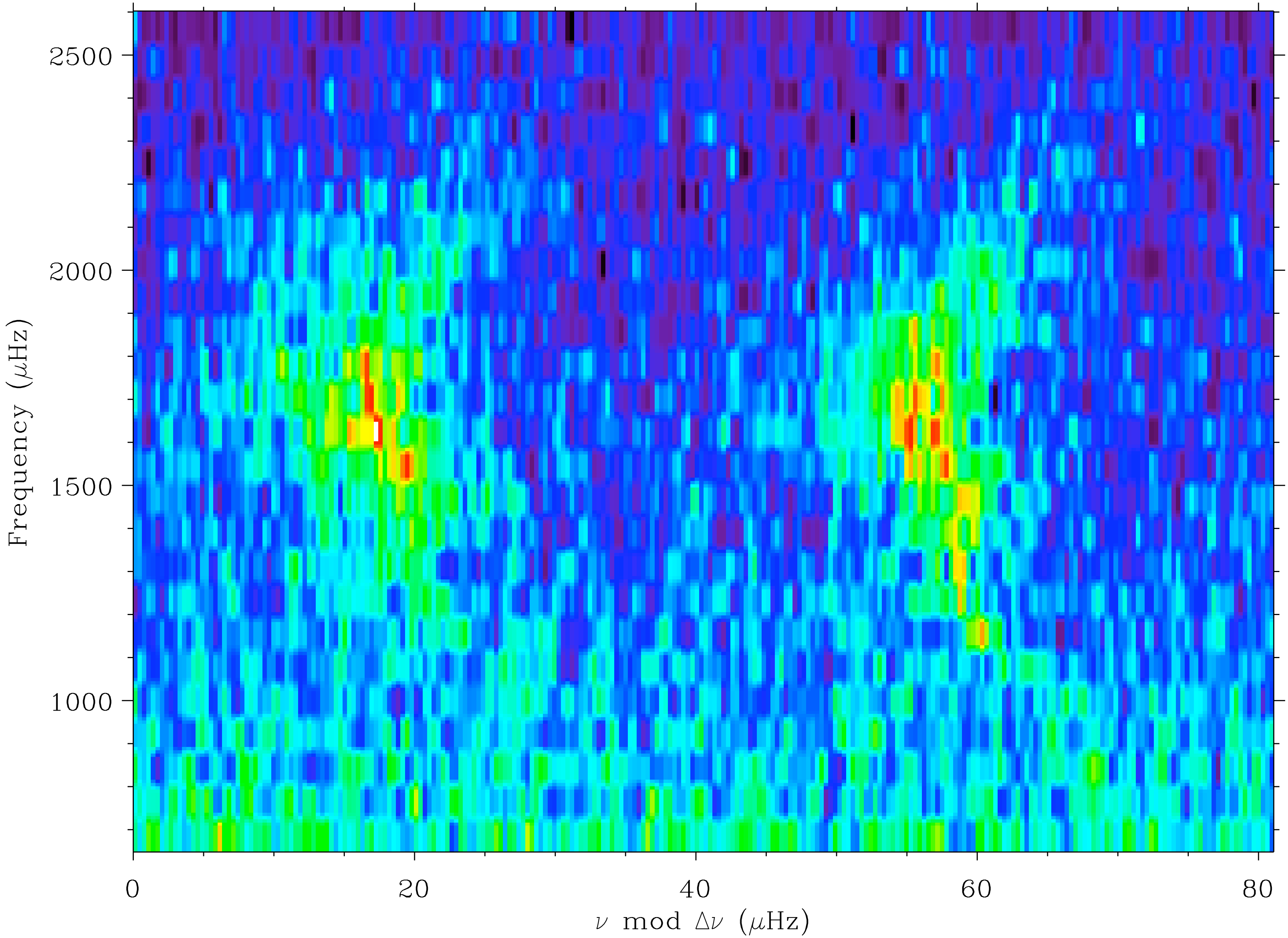
80
100
ν mod Δν (μHz)



2500
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1500
1000
Frequency (μHz)
0
20
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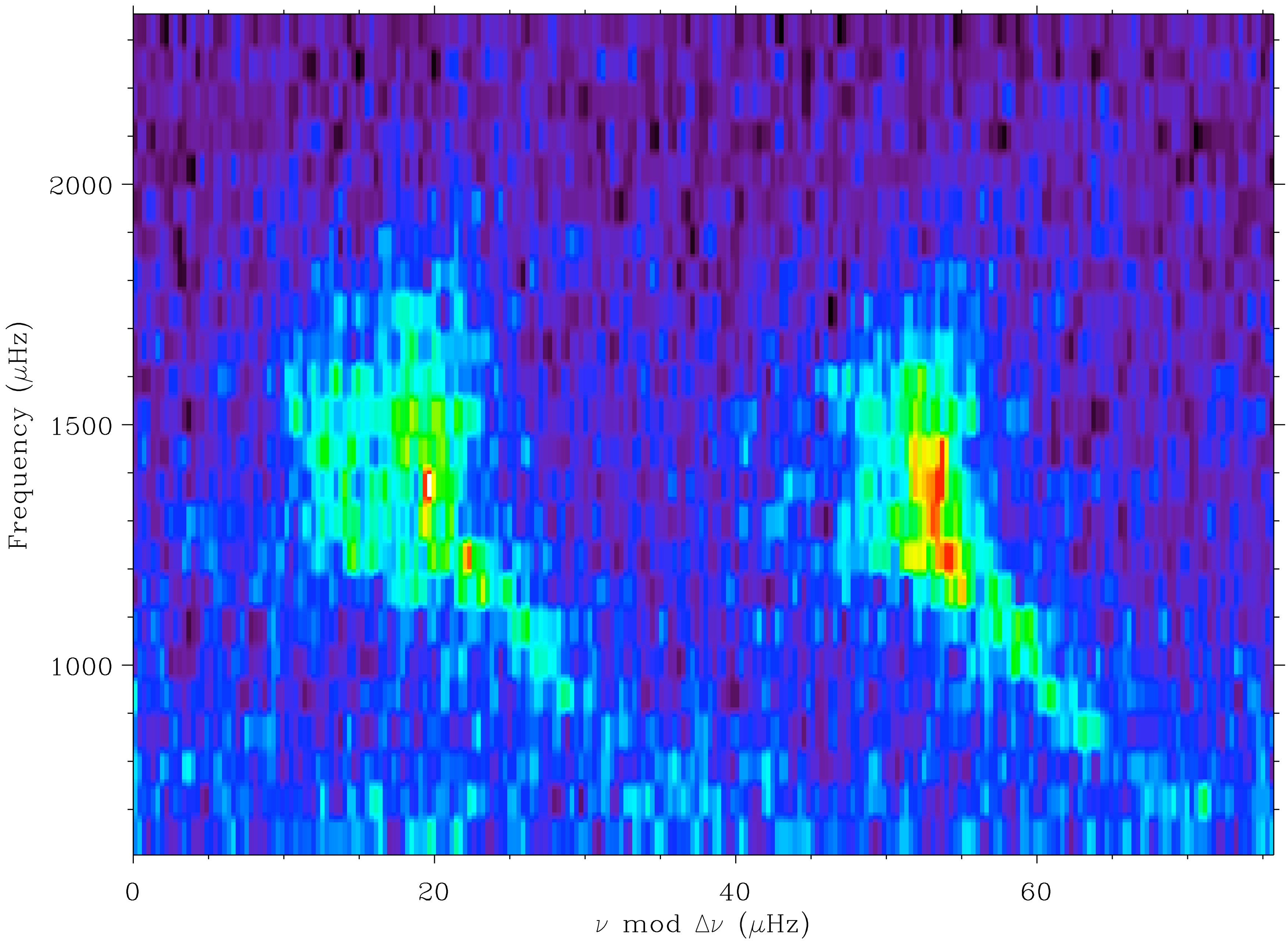
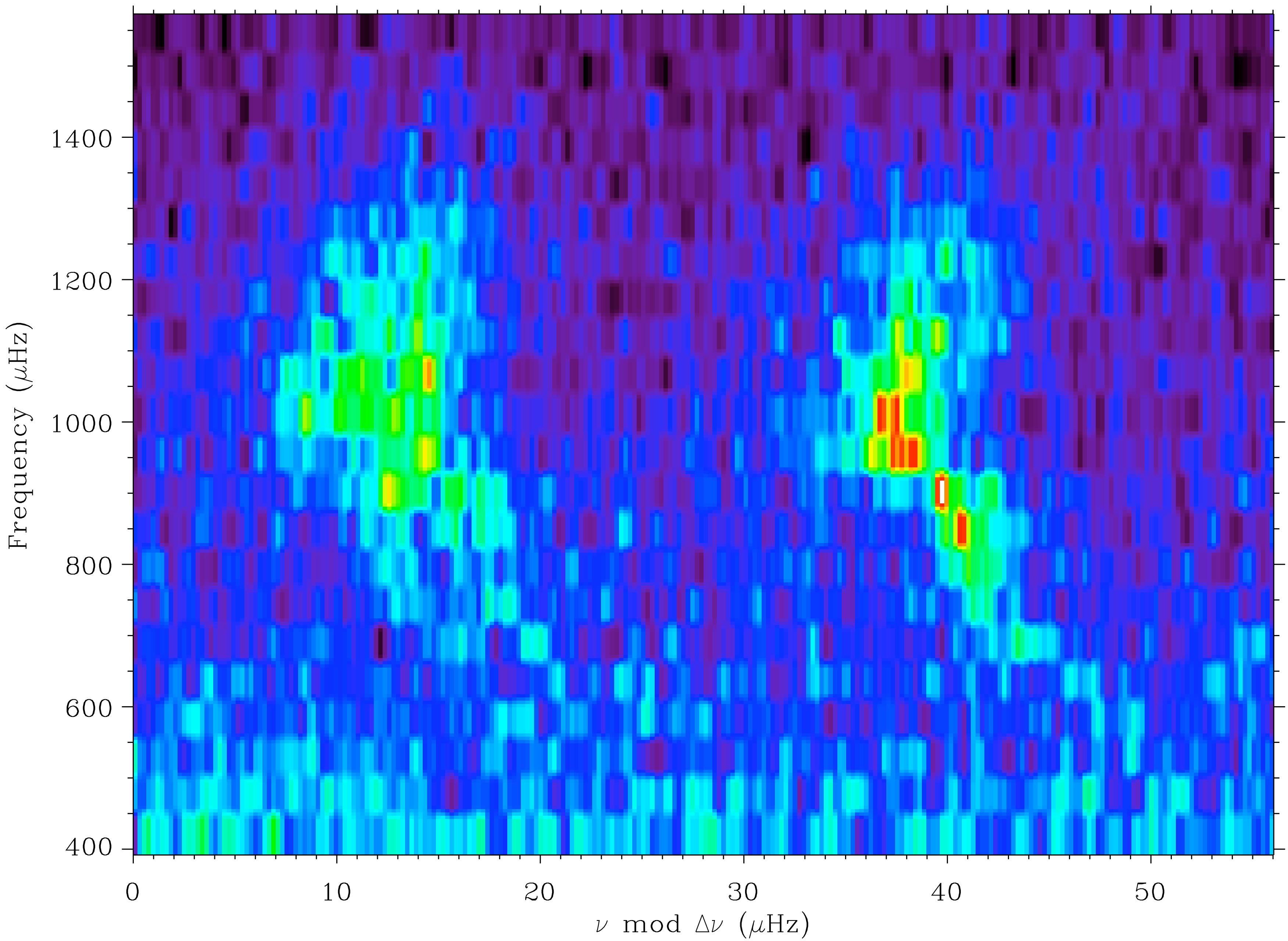
60
80
ν mod Δν (μHz)



2000
1500
1000
Frequency (μHz)
0
20
40
60
ν mod Δν (μHz)



Frequency (μHz)
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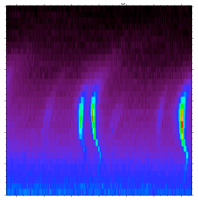
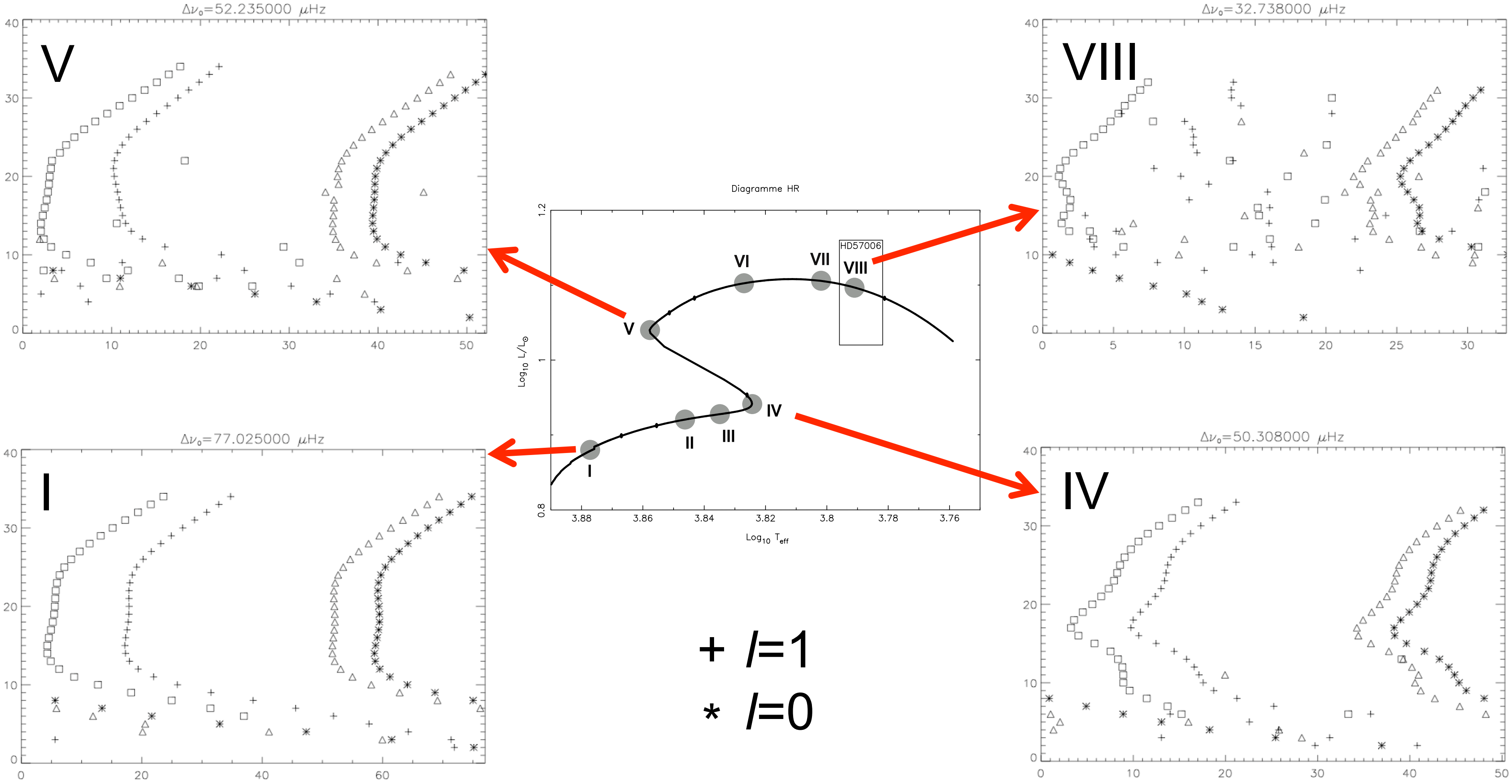
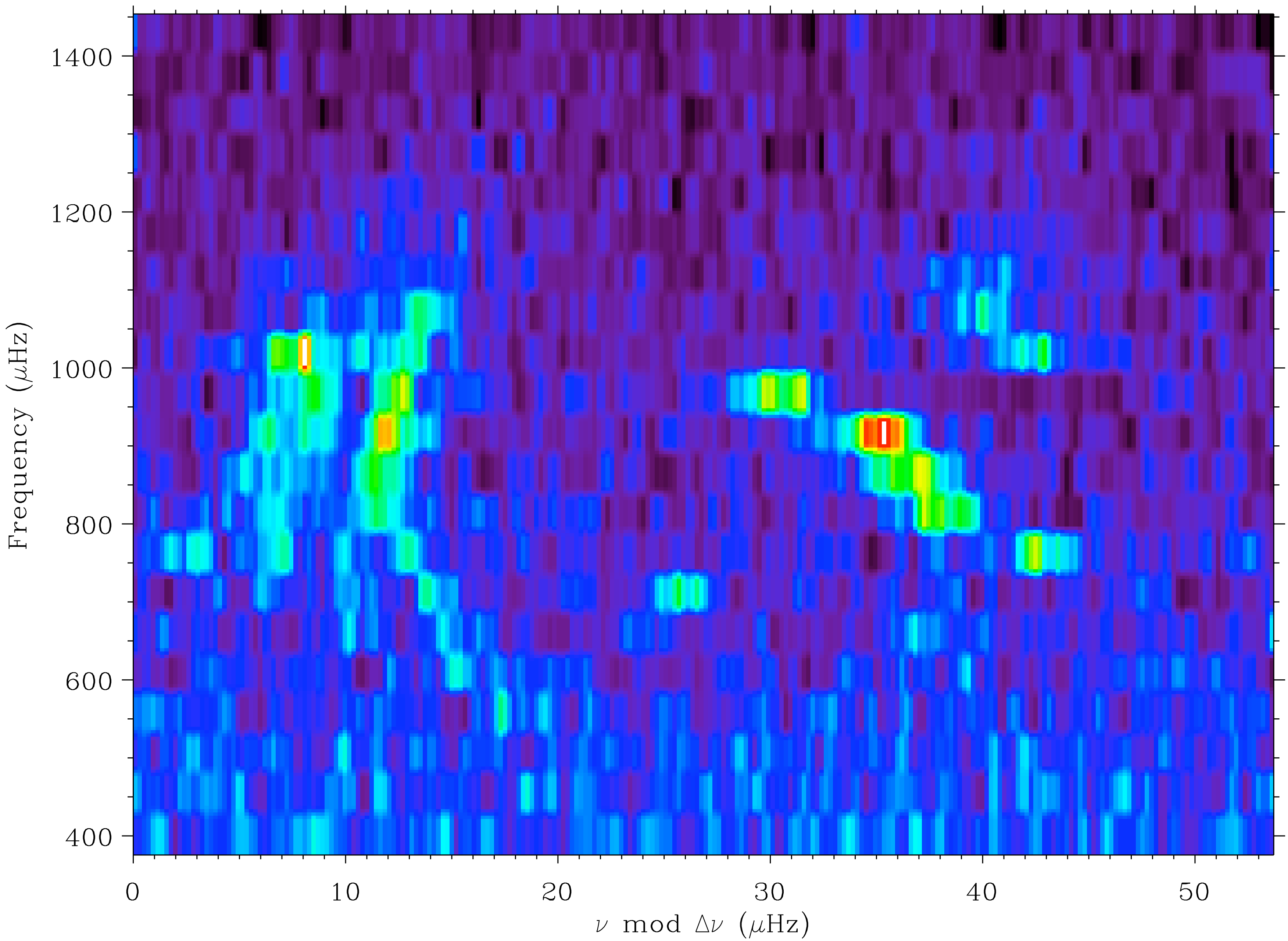
1200
1000
800
600
400
0
10
20
30
40
50
ν mod $\Delta\nu$ (μHz)



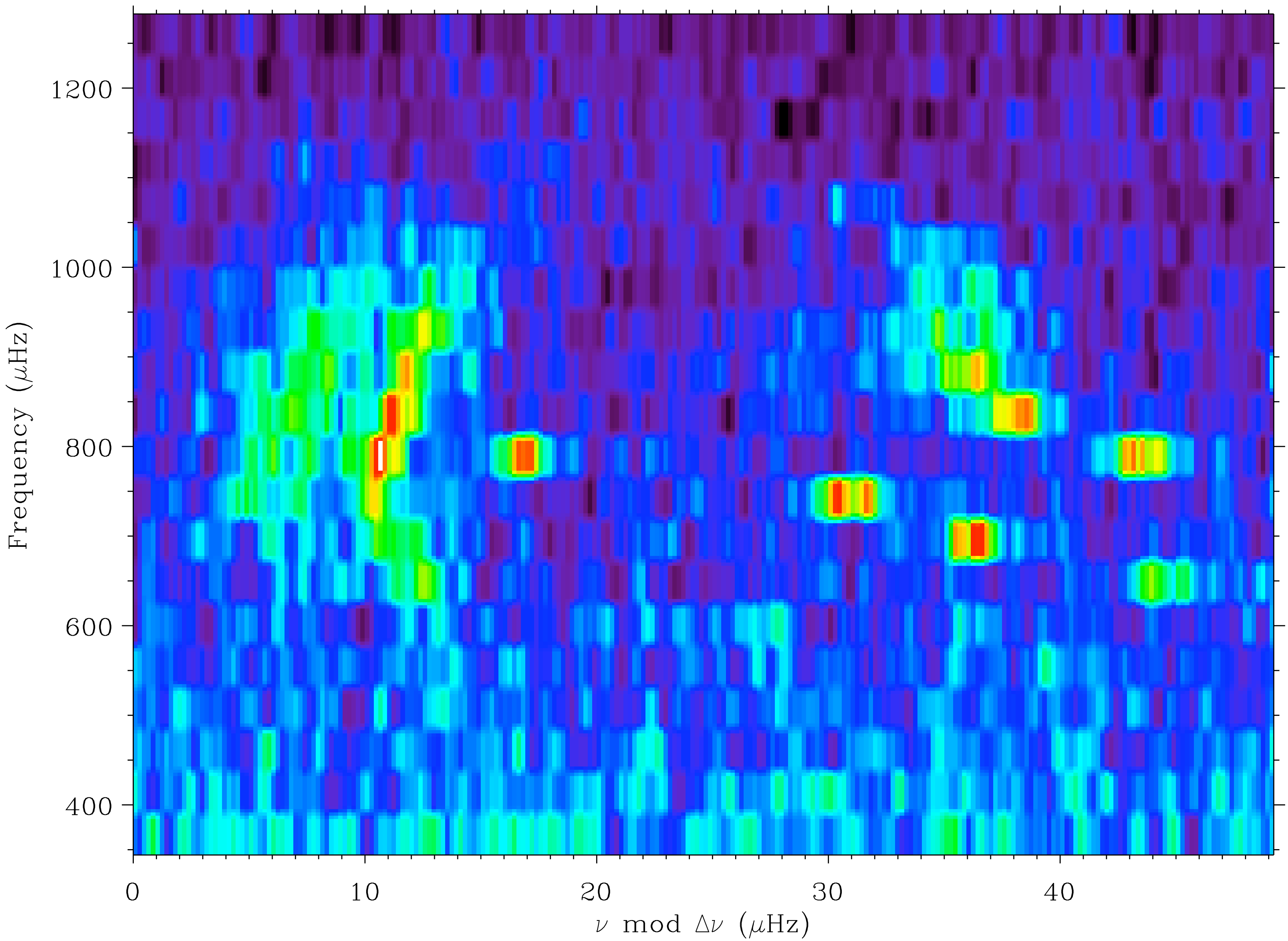
Mixed modes / avoided crossing



Appourchaux et al (2004)



1400
1200
1000
800
600
400
Frequency (μHz)
0
10
20
30
40
50
ν mod Δν (μHz)


1200
1000
800
600
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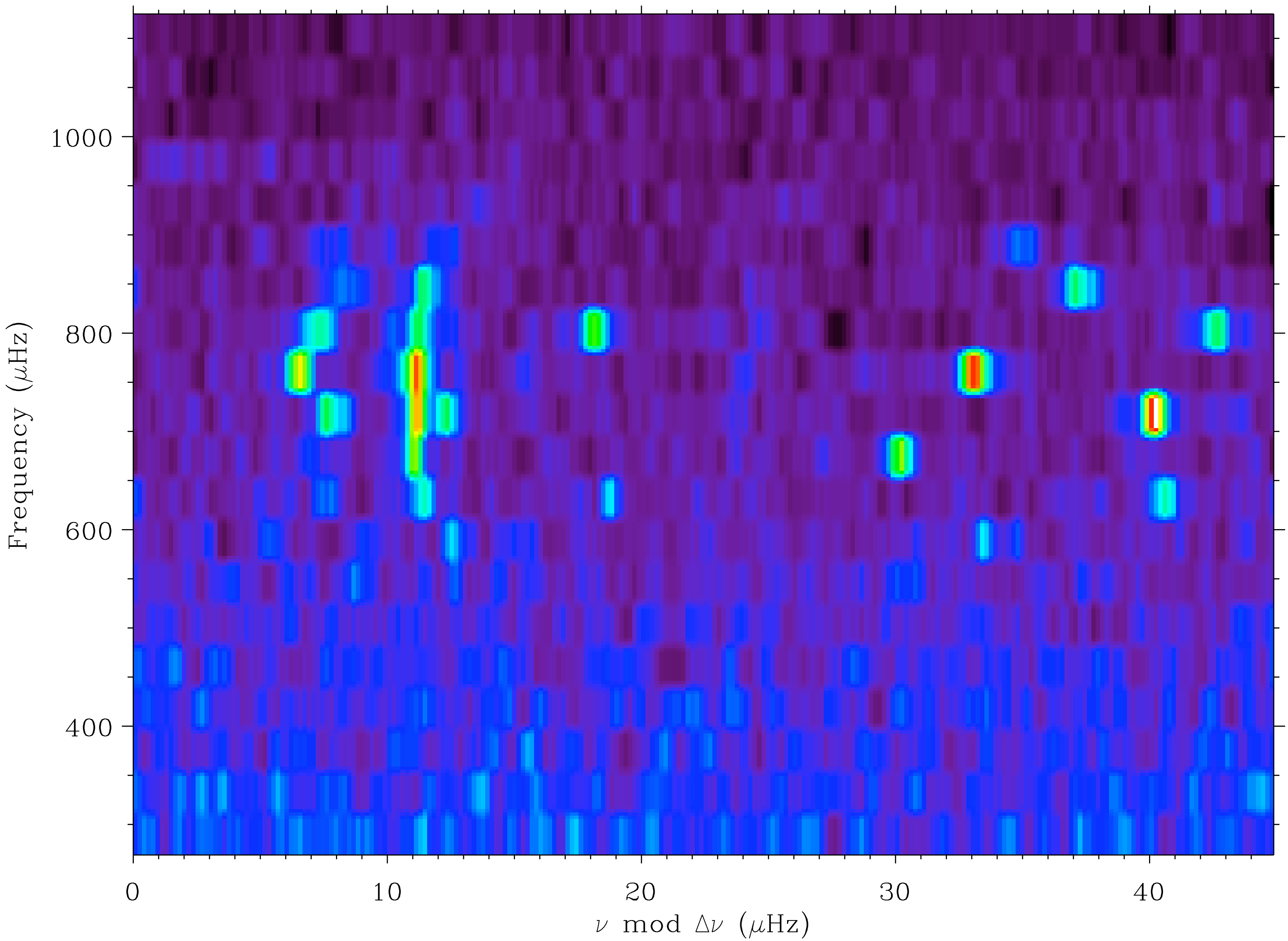
Frequency (μHz)
0
10
20
30
40
ν mod Δν (μHz)



1000
800
600
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Frequency (μHz)
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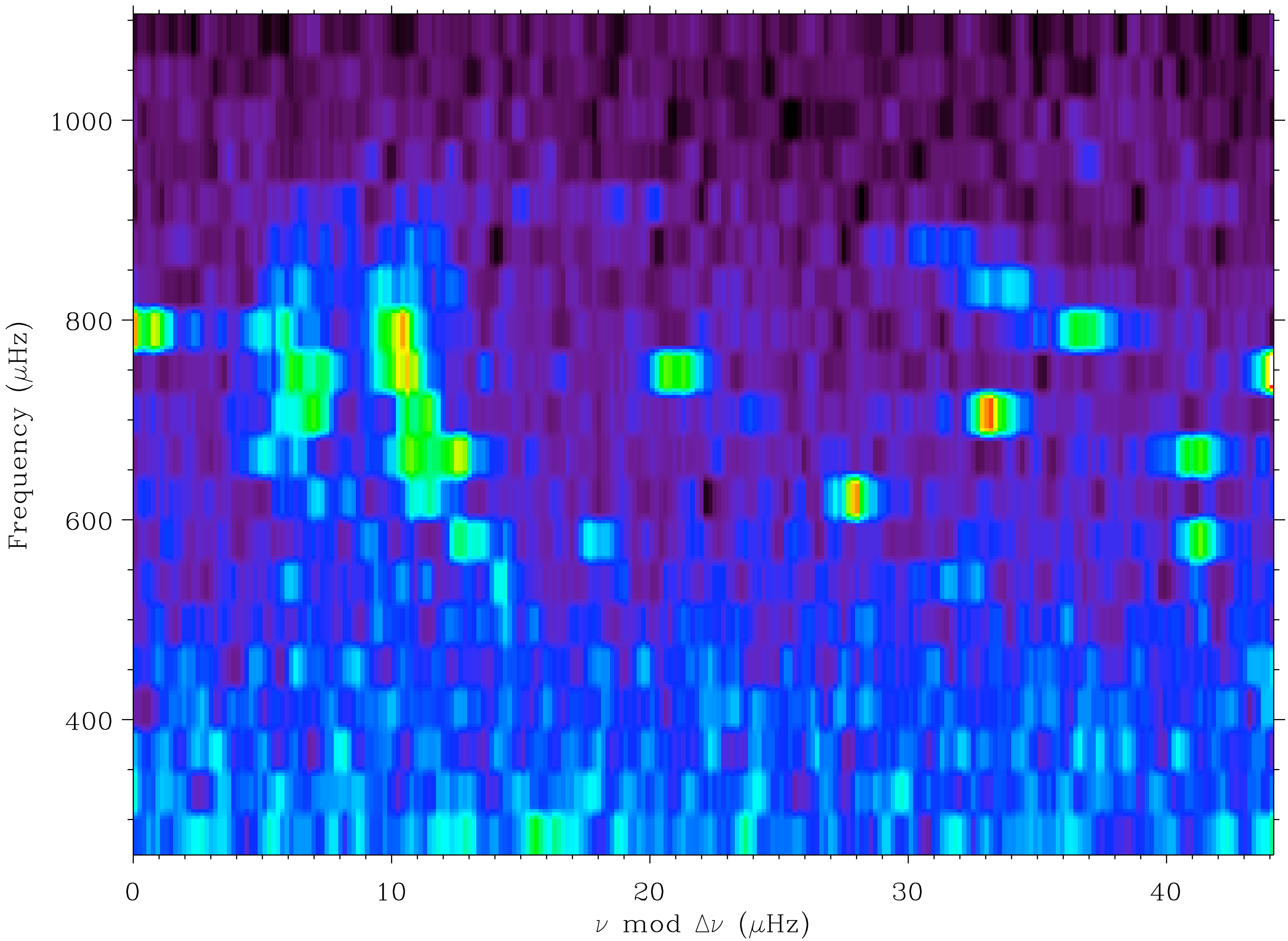
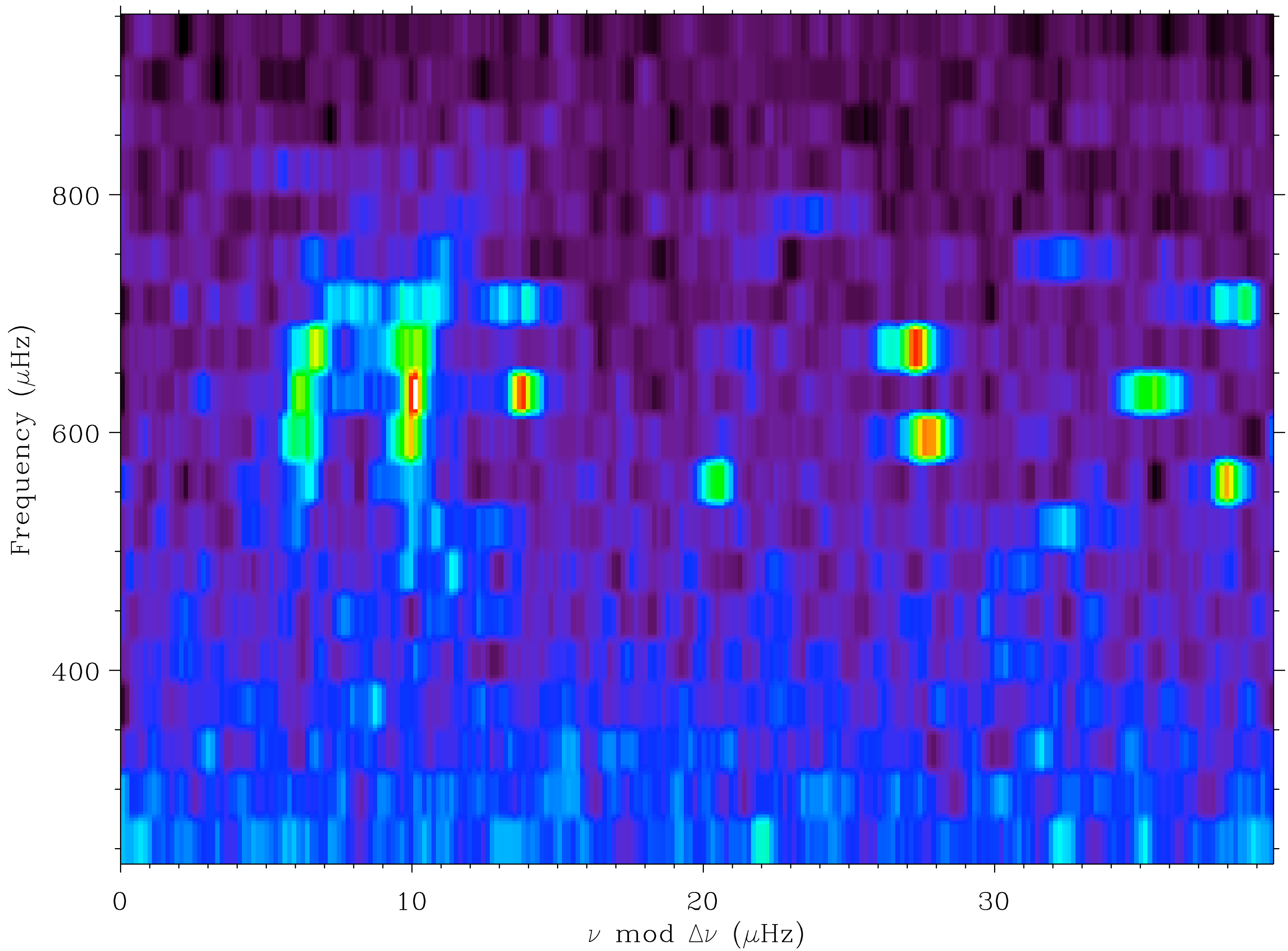
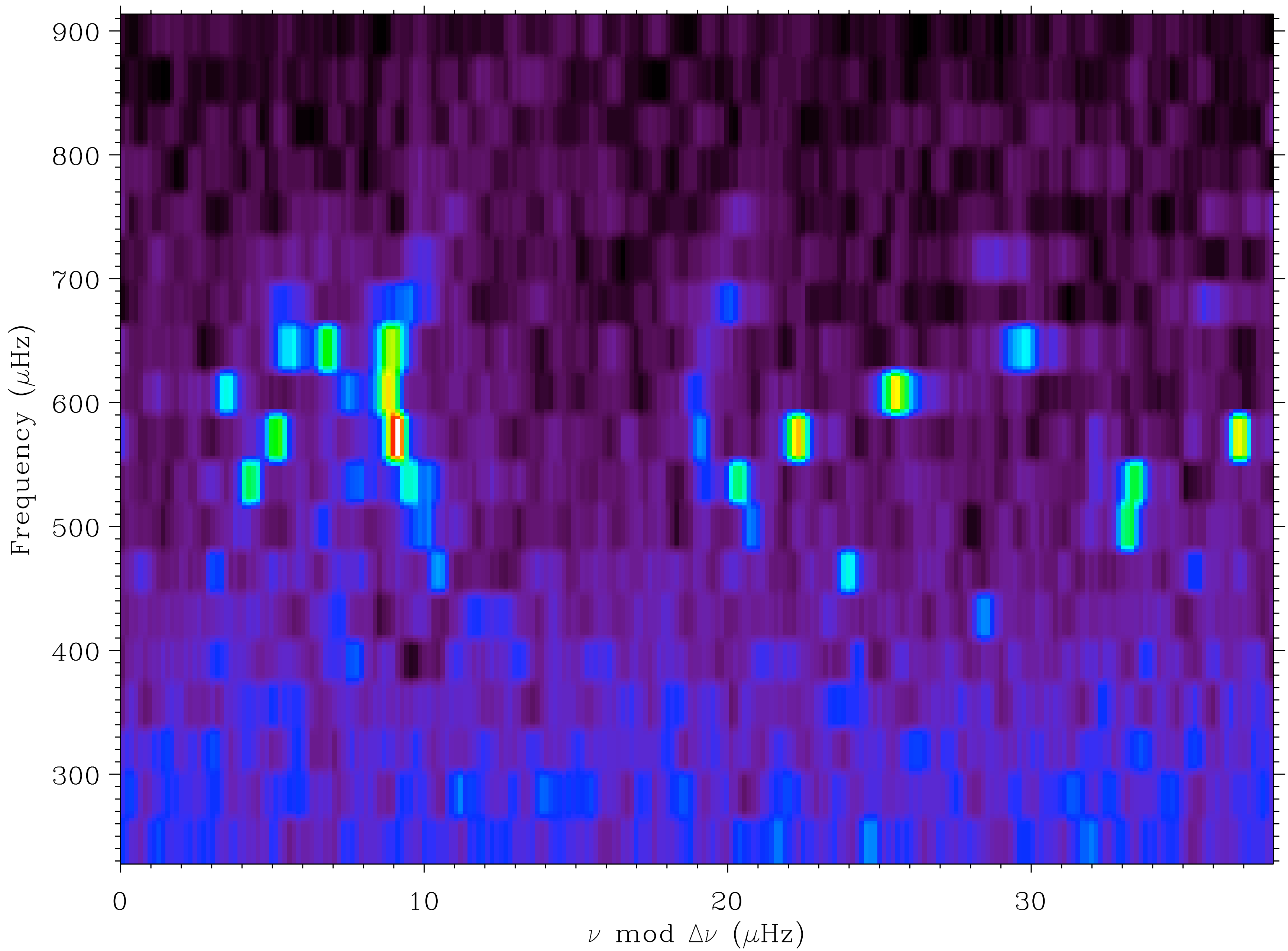
40
ν mod Δν (μHz)



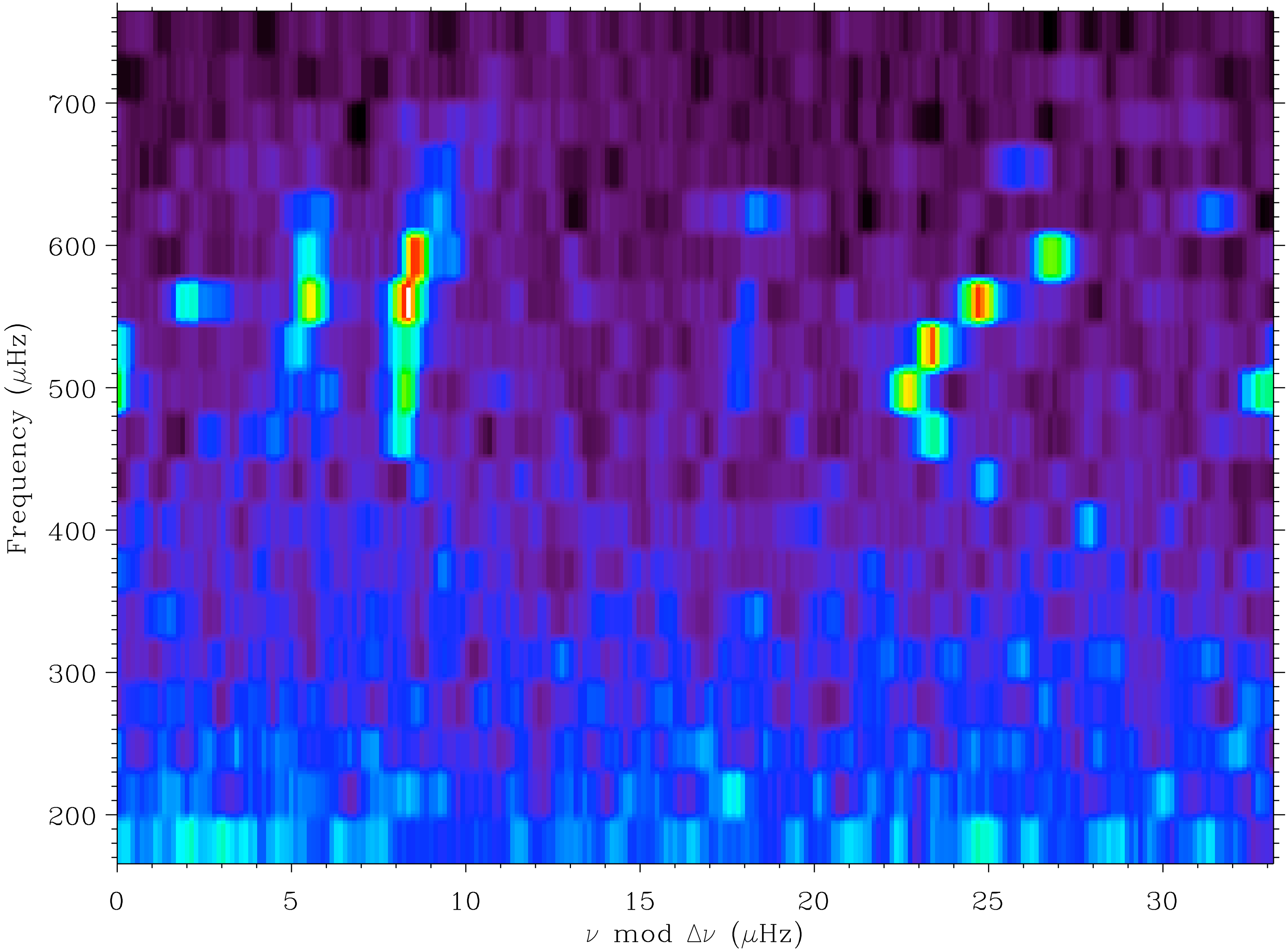
1000
800
600
400
Frequency (μHz)
0
10
20
30
40
ν mod Δν (μHz)



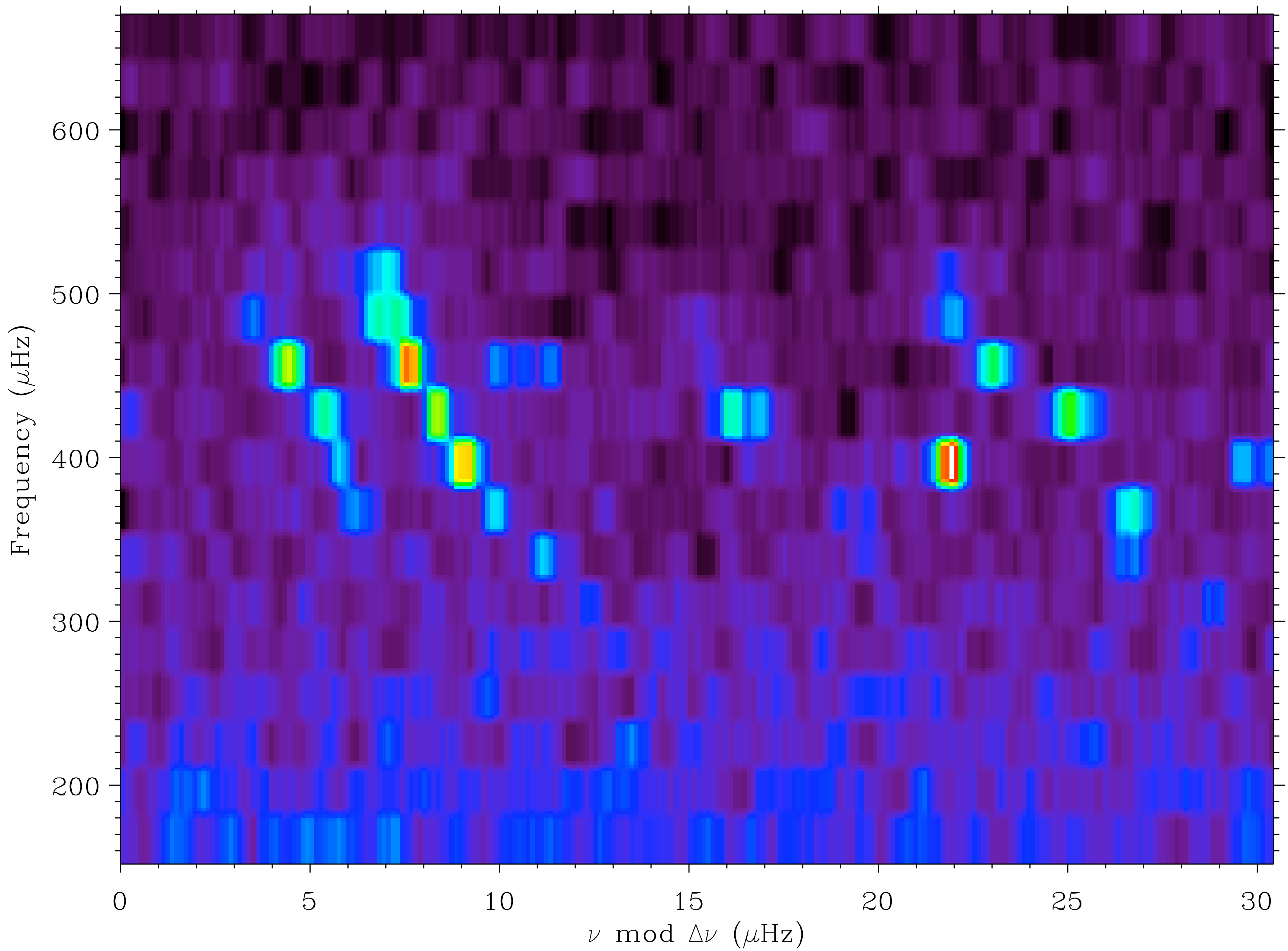
800
600
400
Frequency (μHz)
0
10
20
30
ν mod Δν (μHz)



900
800
700
600
500
400
300
Frequency (μHz)
0
10
20
30
ν mod Δν (μHz)



700
600
500
400
300
200
Frequency (μHz)
0
5
10
15
20
25
30
ν mod Δν (μHz)



Frequency (μHz)
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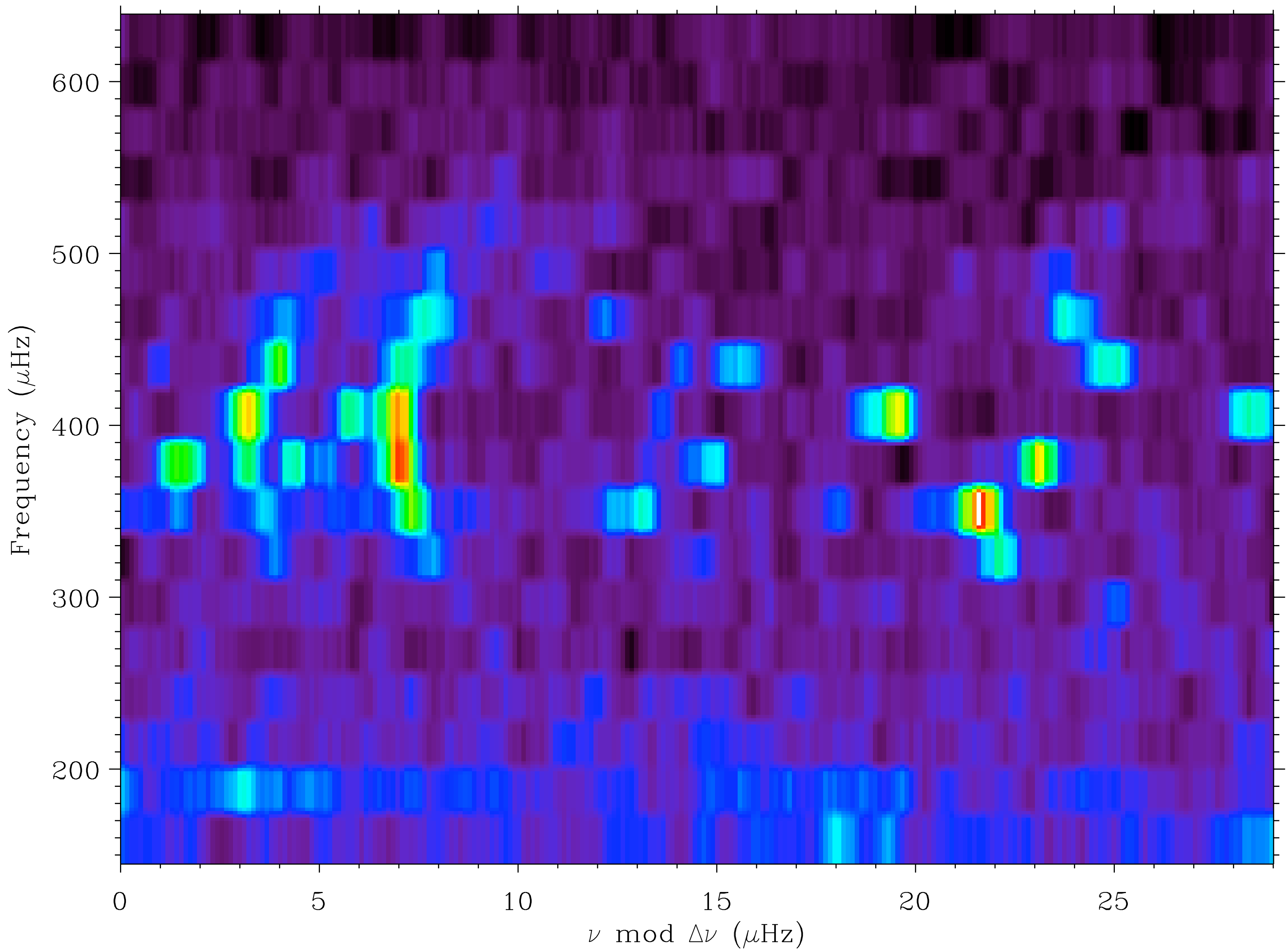
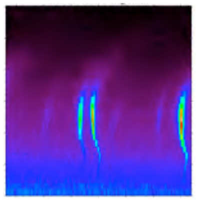
500
400
300
200
0
5
10
15
20
25
30
ν mod Δν (μHz)

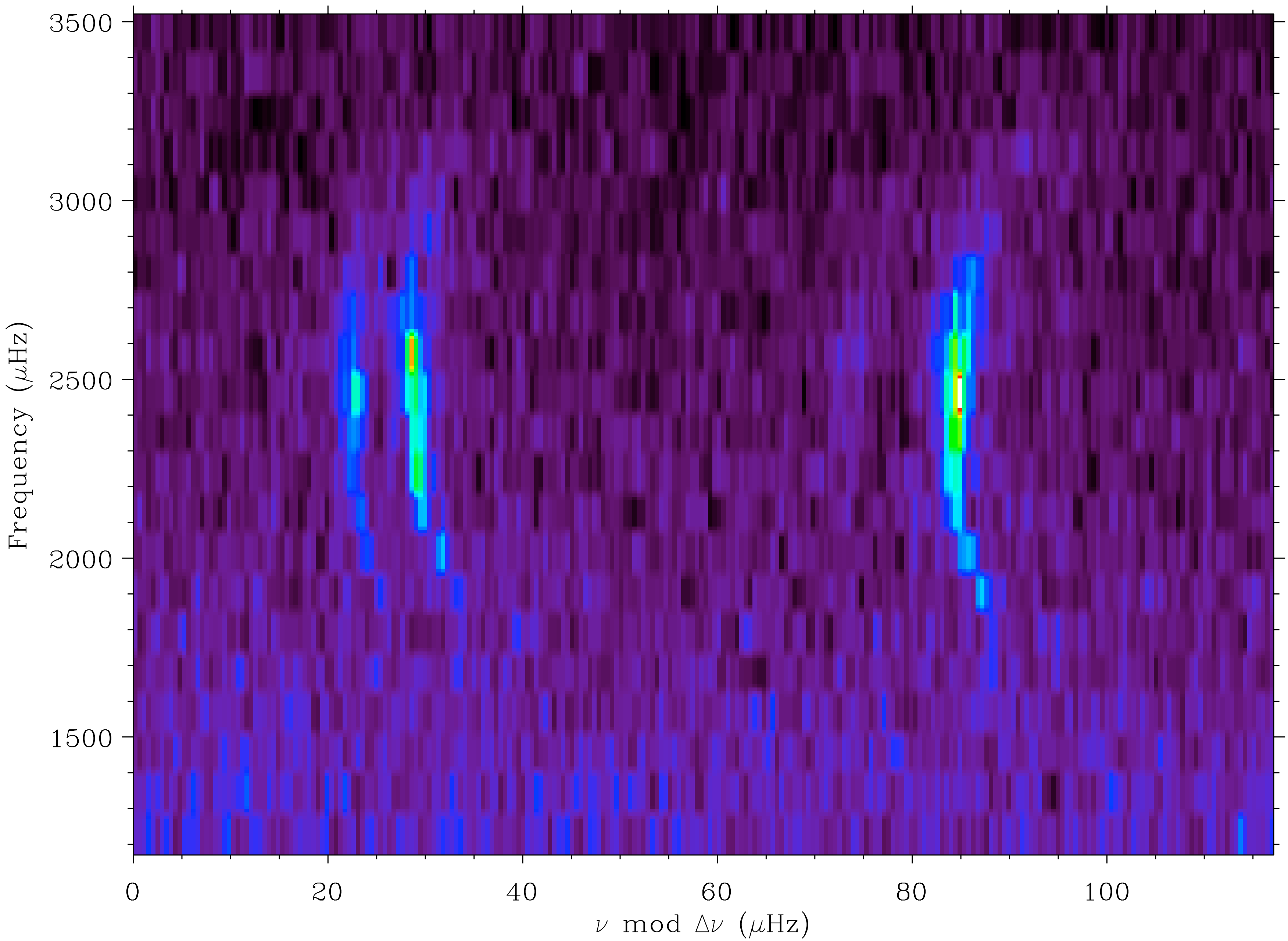


600
500
400
300
200
Frequency (μHz)
0
5
10
15
20
25
ν mod Δν (μHz)



A few results for binary stars
from
current space missions

Waves and Physics, Baia della Zaggare


3500
3000
2500
2000
1500
Frequency (μHz)
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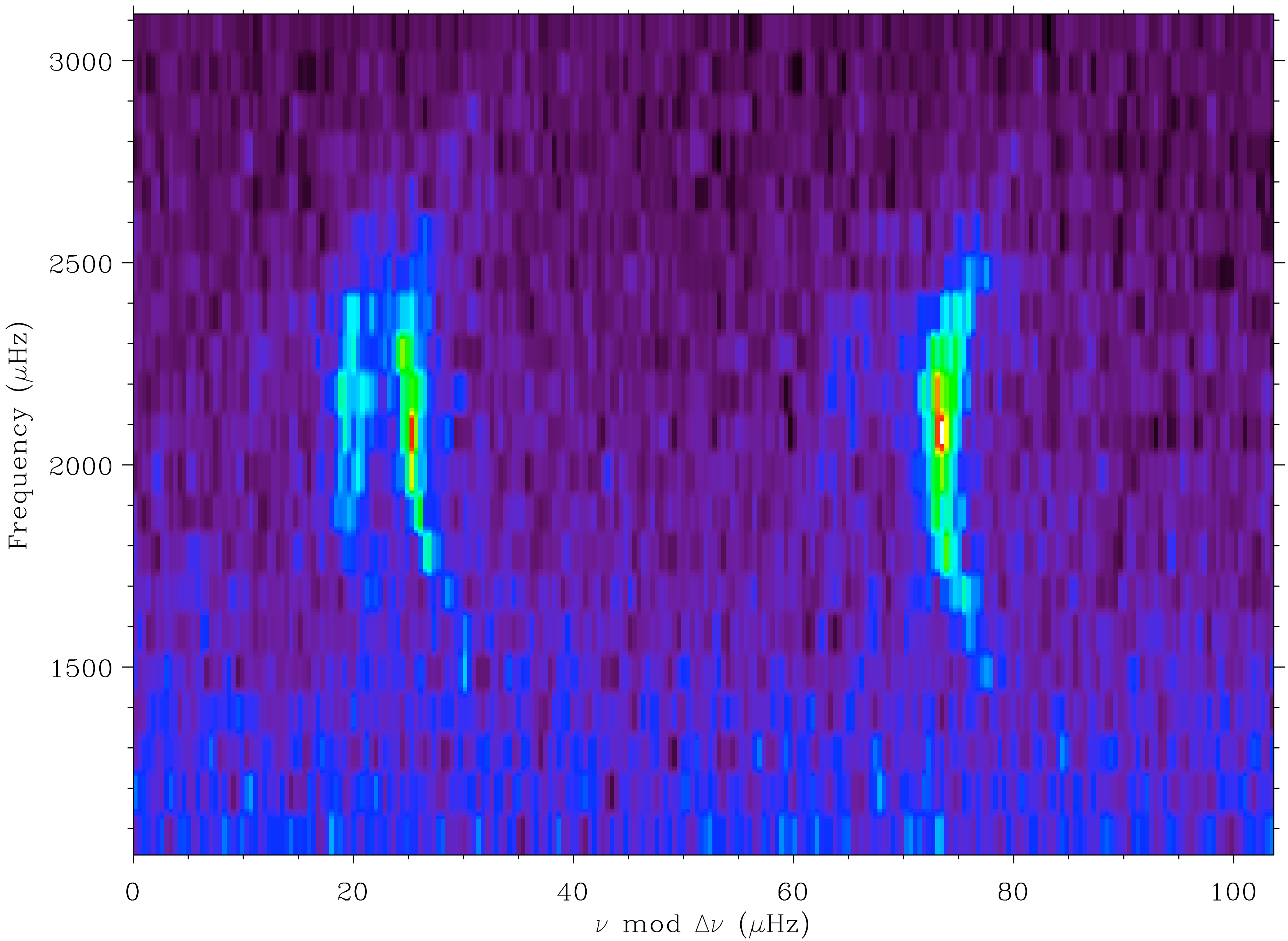
20
40
60
80
100
ν mod Δν (μHz)



3000
2500
2000
1500
Frequency (μHz)
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20
40
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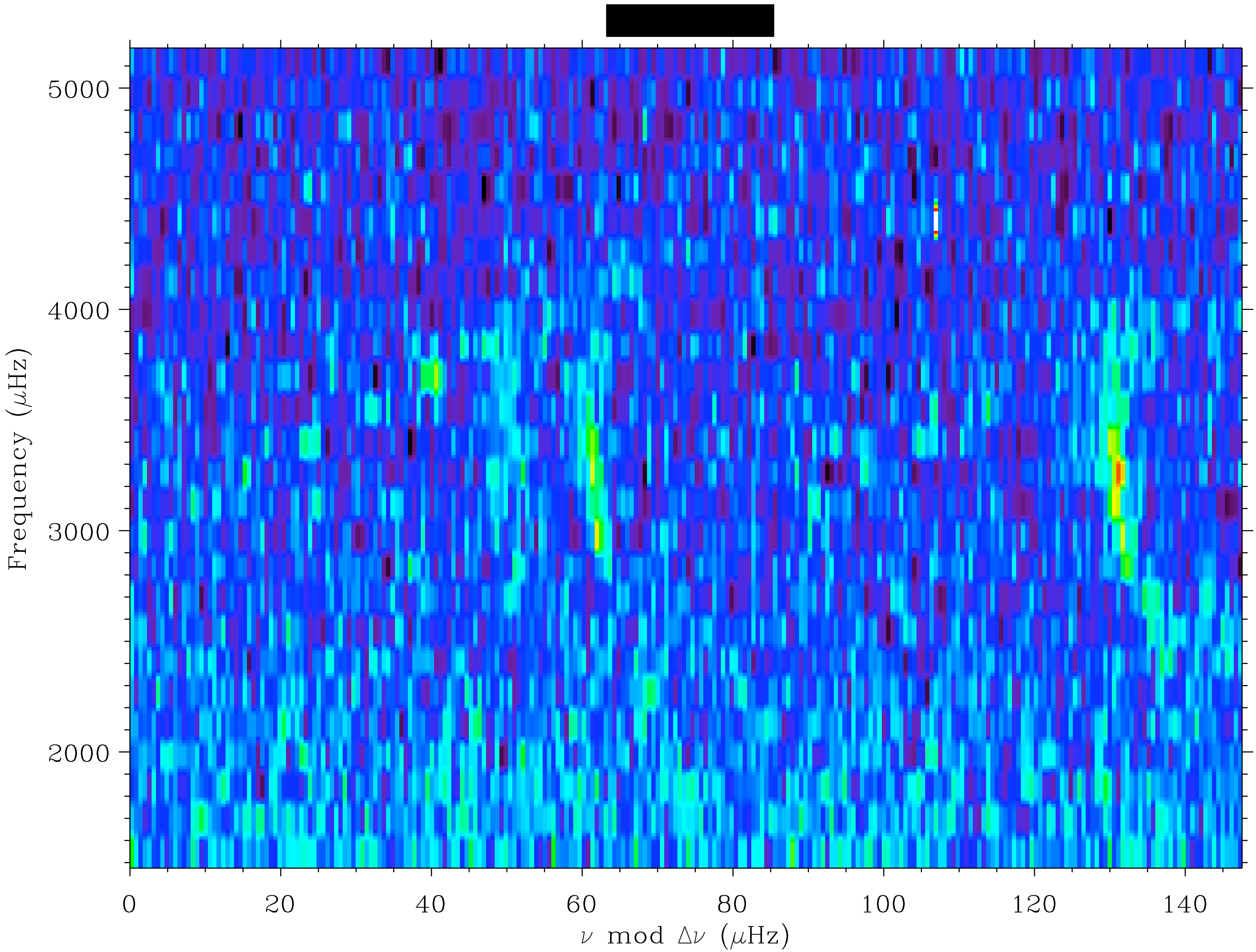
80
100
ν mod Δν (μHz)


[redacted]
Frequency (μHz)
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2000
0
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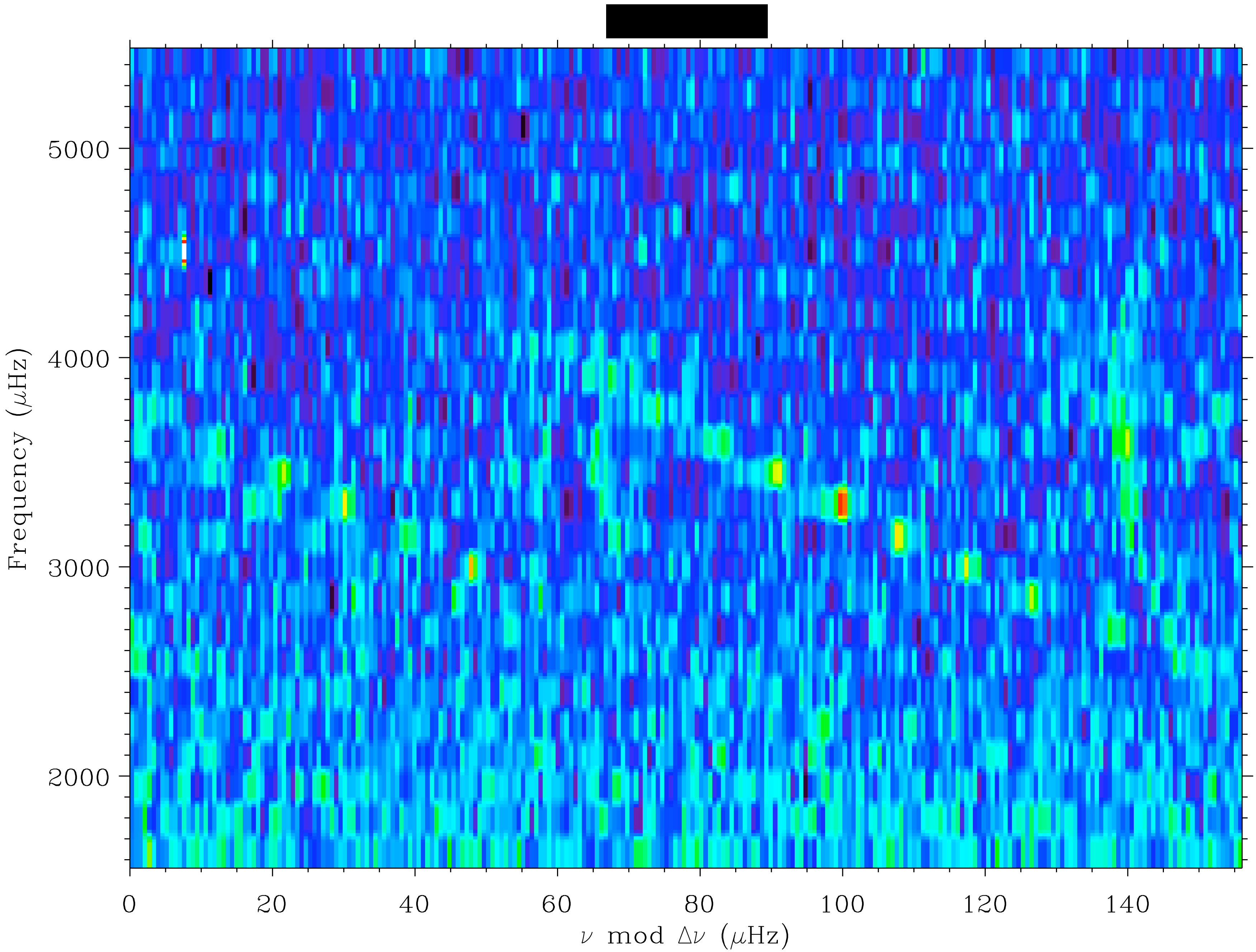
60
80
100
120
140
ν mod Δν (μHz)


[redacted]
Frequency (μHz)
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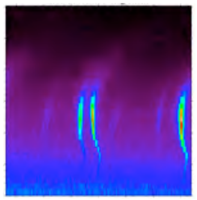
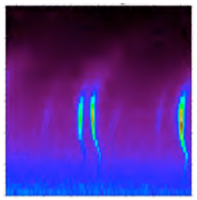
4000
3000
2000
0
20
40
60
80
100
120
140
ν mod Δν (μHz)

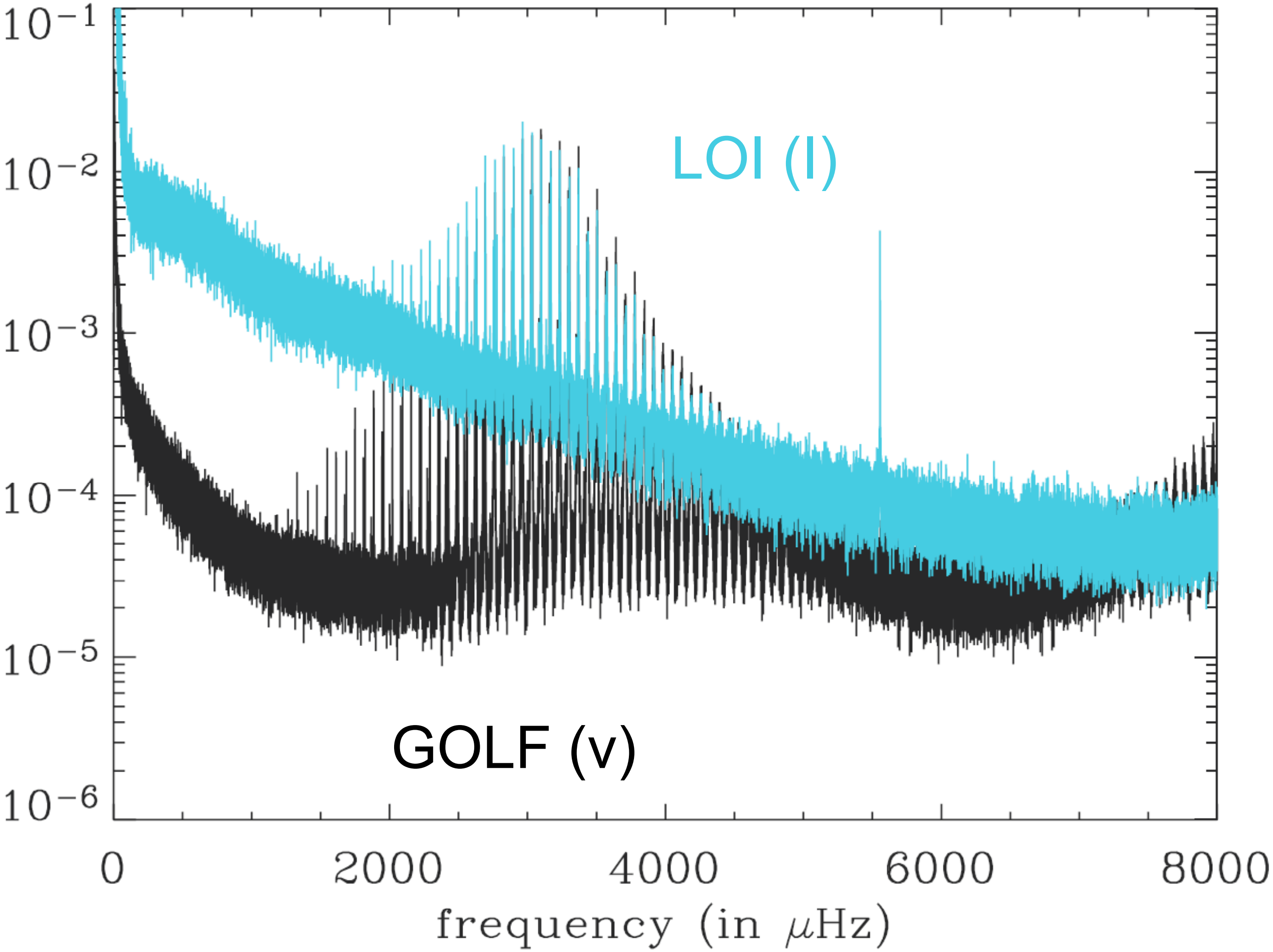


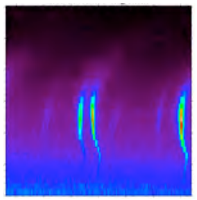
Results for solar-like stars in clusters
from
current space missions...to come...with PLATO

Waves and Physics, Baia della Zaggare



Sun-as-a-star power spectra (I, *v*)





Solar linewidths

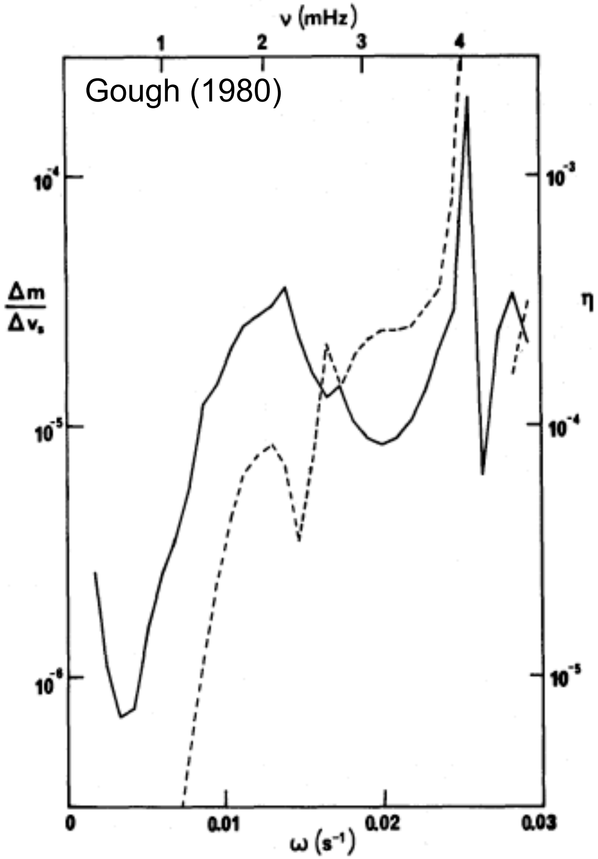


Figure 3. Magnitude-velocity amplitude ratios and stability coefficients of the first 32 radial eigenmodes of a solar model, plotted against frequency. The amplitude ratios $\Delta m/\Delta v_s$ are connected by straight continuous lines; the amplitudes are corrected by the spatial filter functions appropriate for whole-disk measurements (cf. Hill 1978), and velocity is measured in m s^{-1}. The stability coefficients η are the ratios of the decay rates to the angular frequencies of the eigenmodes. Positive values are connected by dashed lines; p_{29} and p_{30} were found to be unstable.

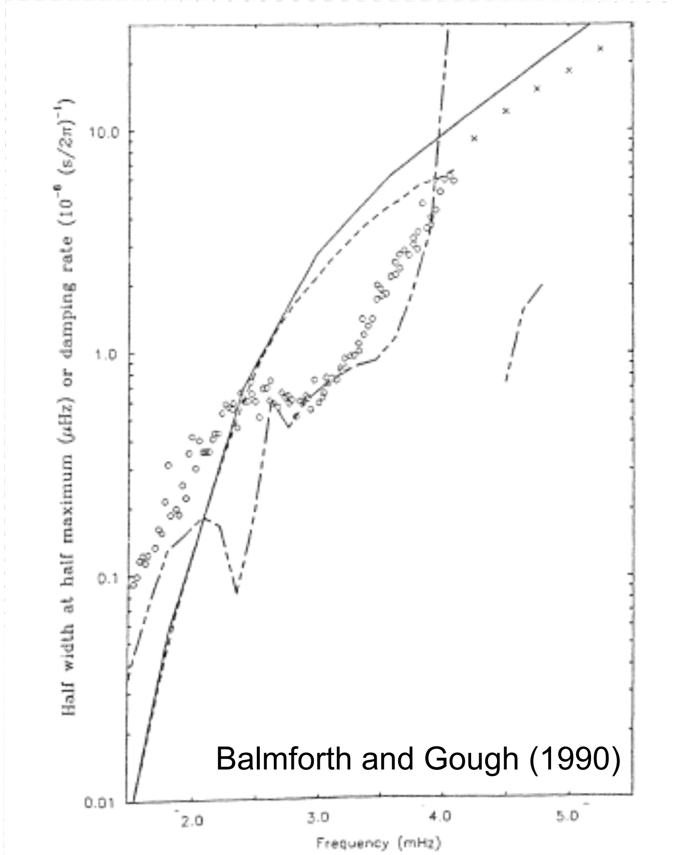
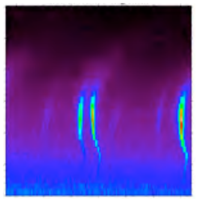


Fig. 1. Observations of solar line widths of Libbrecht (1988a). The curves drawn are the theoretical estimates of damping rates of acoustic oscillations by Christensen-Dalsgaard and Frandsen (1983a, solid curve), Kidman and Cox (1984, dashed line), and Gough (1980, broken dashed line). The growth rates are plotted in units of 10^{-6} $(s/2\pi)^{-1}$ which corresponds to the cyclic frequency unit μHz.



Solar linewidths

A striking feature in the observations is a local maximum of the damping rate at about 2.2 mHz followed by a local minimum at about 2.6 mHz. Interestingly, our theoretical curves also have a similar feature. Again the oscillations due to the mixing-length theory are visible, and the observed feature corresponds to what appears to be the first and broadest oscillation.

Granulation, as observed at the solar surface, is characterized by turnover times which are consistent with mixing-length theory, if the values of the convective velocity, w, and mixing length, l_c, near the edge of the convection zone are used to estimate a characteristic timescale. The convective growth rate, σ, in mixing-length theory is given by

$$w = \sigma l_c / 2 \,. \qquad (16)$$

Therefore, the characteristic mixing-length frequency is just $2w/l_c$.

At the maximum of the peak in the temperature gradient, ∇, in the hydrogen ionization zone, where convective effects might be most dominant, the values of w and l_c for a typical model envelope give a characteristic frequency, $\nu_c \simeq 2.5$ mHz, which is close to the frequency at which the minimum in the damping rate occurs. It is, therefore, quite possible that this feature is a consequence of the interaction between the locally radial pulsation and the granular motion. Merryfield (1988) has also found such a resonant interaction in an idealized model of convection interacting with acoustic waves.

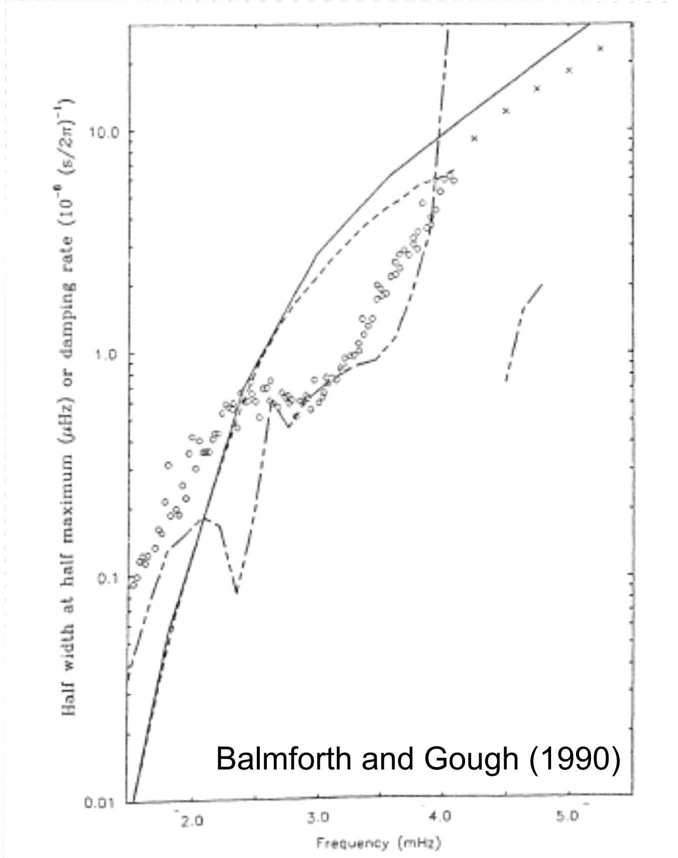


Fig. 1. Observations of solar line widths of Libbrecht (1988a). The curves drawn are the theoretical estimates of damping rates of acoustic oscillations by Christensen-Dalsgaard and Frandsen (1983a, solid curve), Kidman and Cox (1984, dashed line), and Gough (1980, broken dashed line). The growth rates are plotted in units of $10^{-6}\,(s/2\pi)^{-1}$ which corresponds to the cyclic frequency unit μHz.

Stellar linewidths

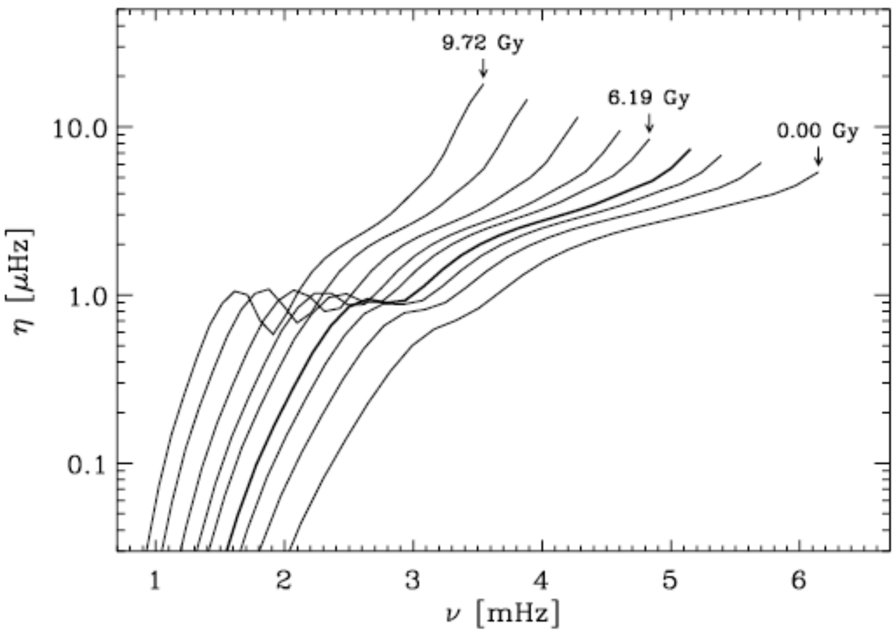


Fig. 3. Damping rates for an evolving $1\,M_\odot$ star as function of frequency. The results are displayed for models with ages=(0, 2.49, 3.96, 4.55, 6.19, 7.00, 8.03, 9.02, 9.72) Gy. The thick curve indicates the results for the present Sun. Values $\alpha = 1.8, a^2 = b^2 = 600$ for the convection parameters have been used.

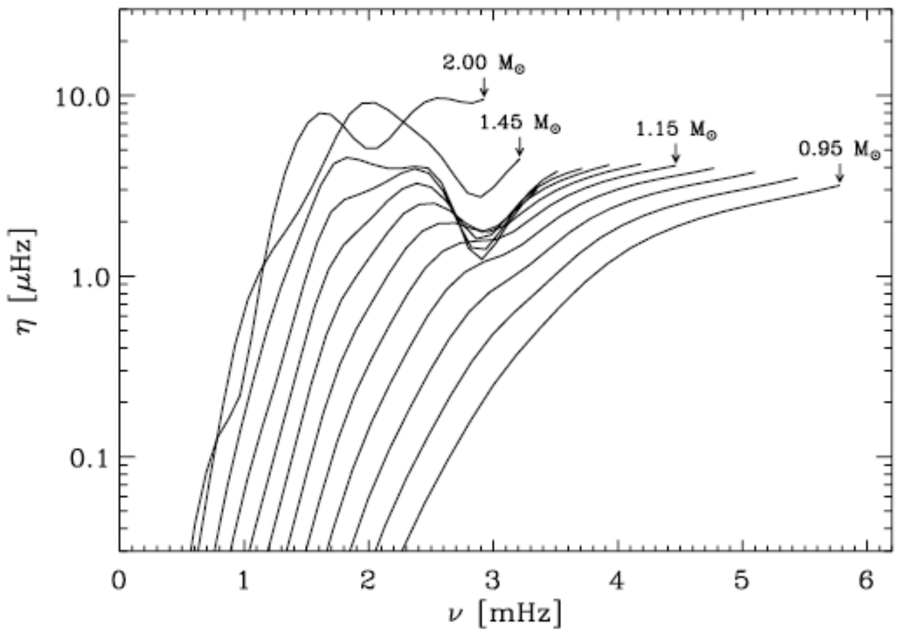
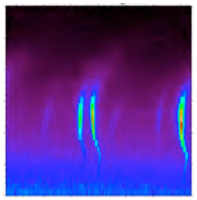


Fig. 5. Damping rates for ZAMS models as functions of frequency. The results are displayed for models with M=(0.95, 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40, 1.45, 2.00) $M_\odot$. For the convection parameters the values $\alpha = 2.0, a^2 = 900, b^2 = 2000$ have been used.

Houdek et al (1999)



Stellar linewidths

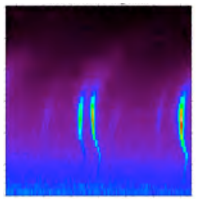
The total damping rate η (solid curve), plotted as a function of cyclic frequency $\nu = \omega_r/2\pi$, is characteristically flat at frequencies near 2.8 mHz (see Fig. 2). This feature is also observed in solar linewidth measurements (e.g. Libbrecht 1988, Appourchaux et al. 1998, Chaplin et al. 1998). At these frequencies the net damping is reduced particularly by radiative processes in the upper superadiabatic boundary layer of the convection zone, which are locally destabilizing.

The damping rates for an evolving $1\,M_\odot$ star are depicted in Fig. 3. Damping rates generally increase with increasing age, particularly for low- and high-order modes. For modes of intermediate order the flattening of the damping-rate curve becomes more pronounced as the star evolves, and turns into a locally concave function at about the solar age. The maximum value of the superadiabatic temperature gradient of a $1\,M_\odot$ star increases by approximately 24% along the main sequence, promoting the depression in the damping rates.

A similar behaviour of the damping rates is obtained for more massive stars, as indicated for the evolving $1.45\,M_\odot$ star depicted in Fig. 4. For these more massive stars, larger values of the nonlocality parameters, $a^2 = 900$ and $b^2 = 2000$, were adopted. This selection ensured that all the radial modes were stable, in line with our working hypothesis that stochastic excitation underlies the appearance of solar-like oscillations (but see Sect. 9). The depression in the damping rates is more pronounced for these stars, even at the ZAMS. This trend may be seen even more obviously in Fig. 5, where damping rates are depicted for stars with increasing mass along the ZAMS.

see Sect. 9). The depression in the damping rates is more pronounced for these stars, even at the ZAMS. This trend may be seen even more obviously in Fig. 5, where damping rates are depicted for stars with increasing mass along the ZAMS.

Houdek et al (1993)



Linewidths with Kepler

Waves and Physics, Baia della Zaggare

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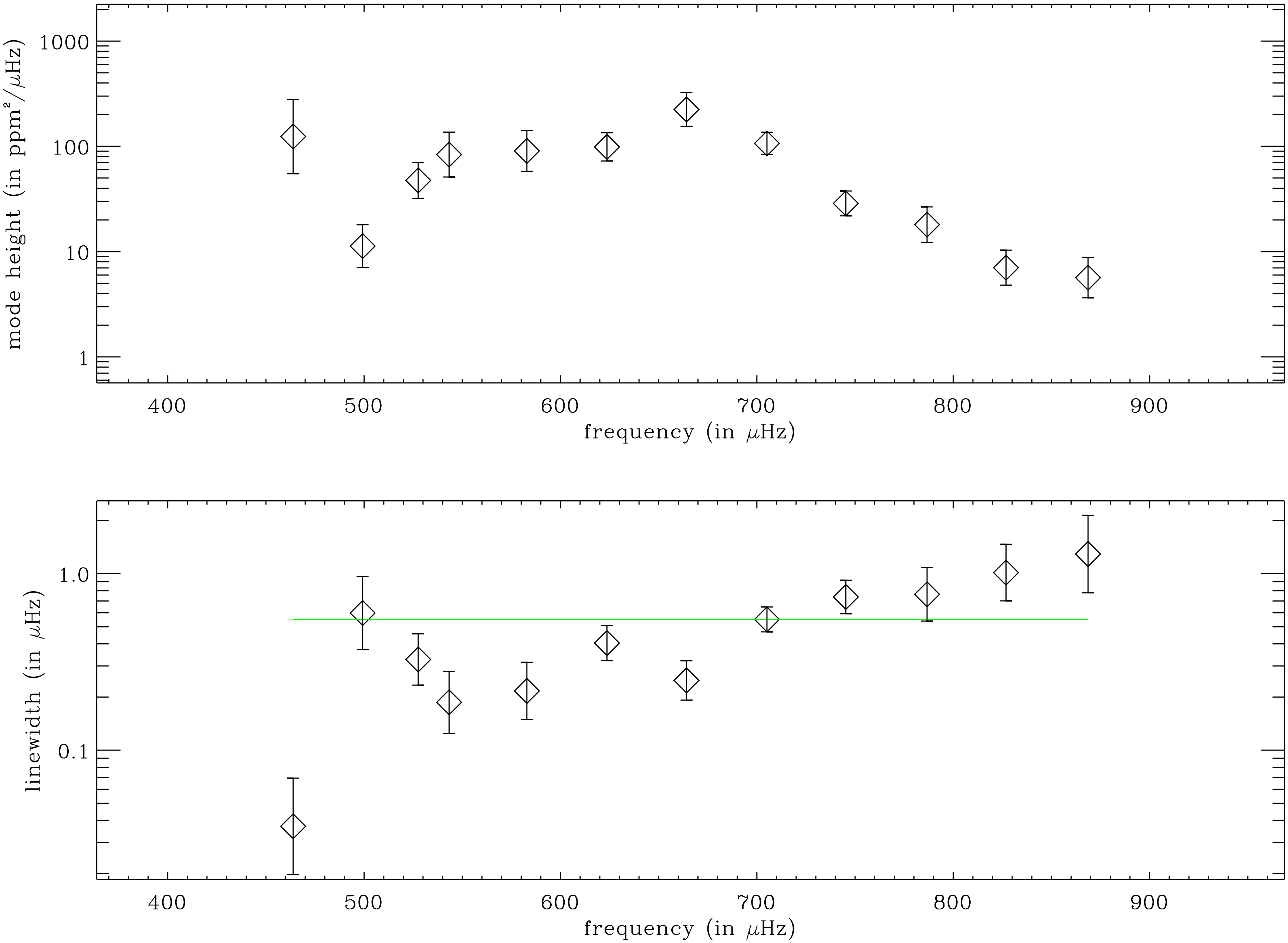

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10
1
400
500
600
700
800
900
frequency (in μHz)
linewidth (in μHz)
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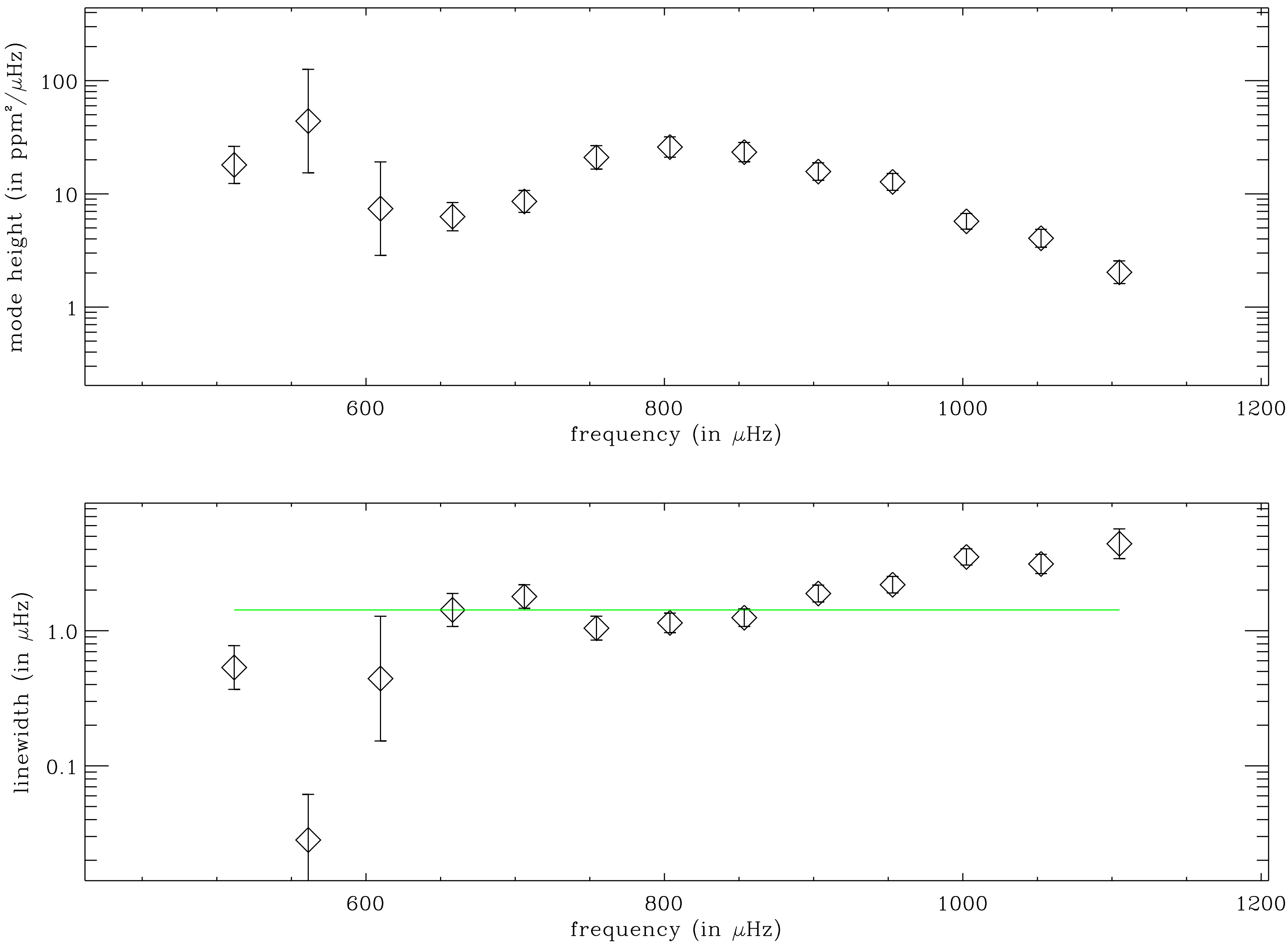
0.1
400
500
600
700
800
900
frequency (in μHz)

[redacted]



100
10
1
mode height (in ppm²/μHz)
600
800
1000
1200
frequency (in μHz)
1.0
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linewidth (in μHz)
600
800
1000
1200
frequency (in μHz)

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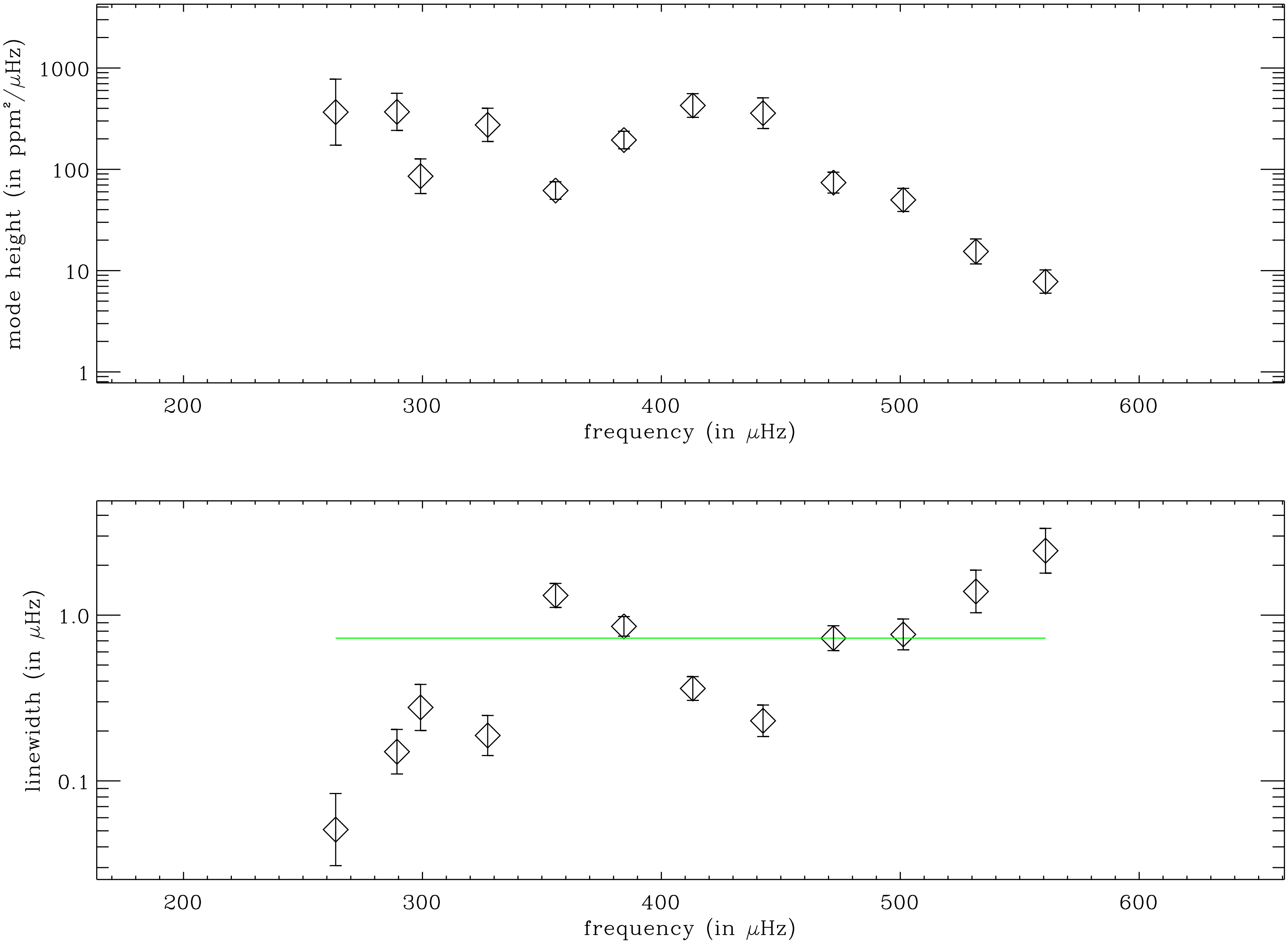

mode height (in ppm²/μHz)
1000
100
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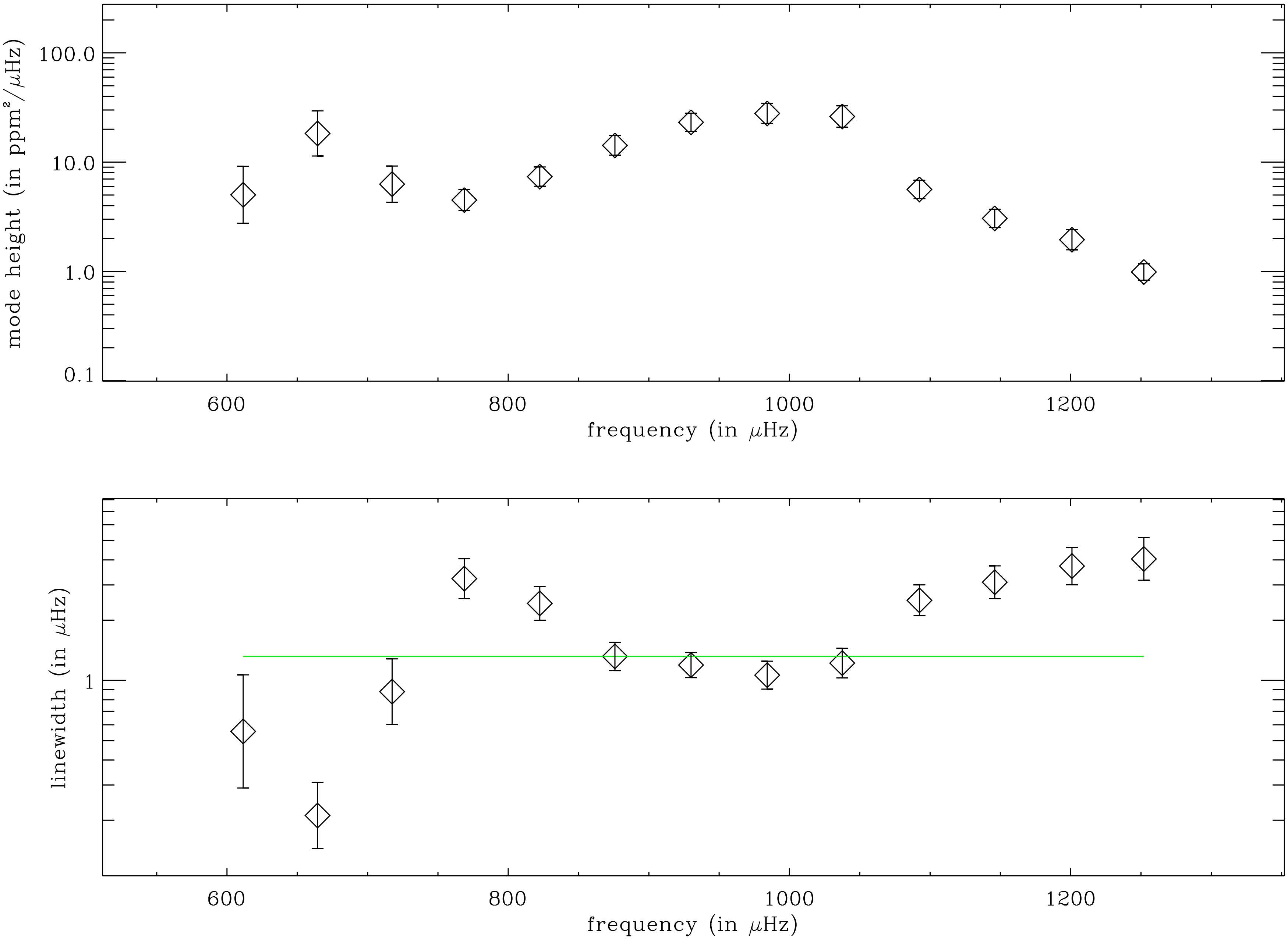
200
300
400
500
600
frequency (in μHz)
linewidth (in μHz)
1.0
0.1
200
300
400
500
600
frequency (in μHz)

[redacted]



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1200
frequency (in μHz)
linewidth (in μHz)
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600
800
1000
1200
frequency (in μHz)

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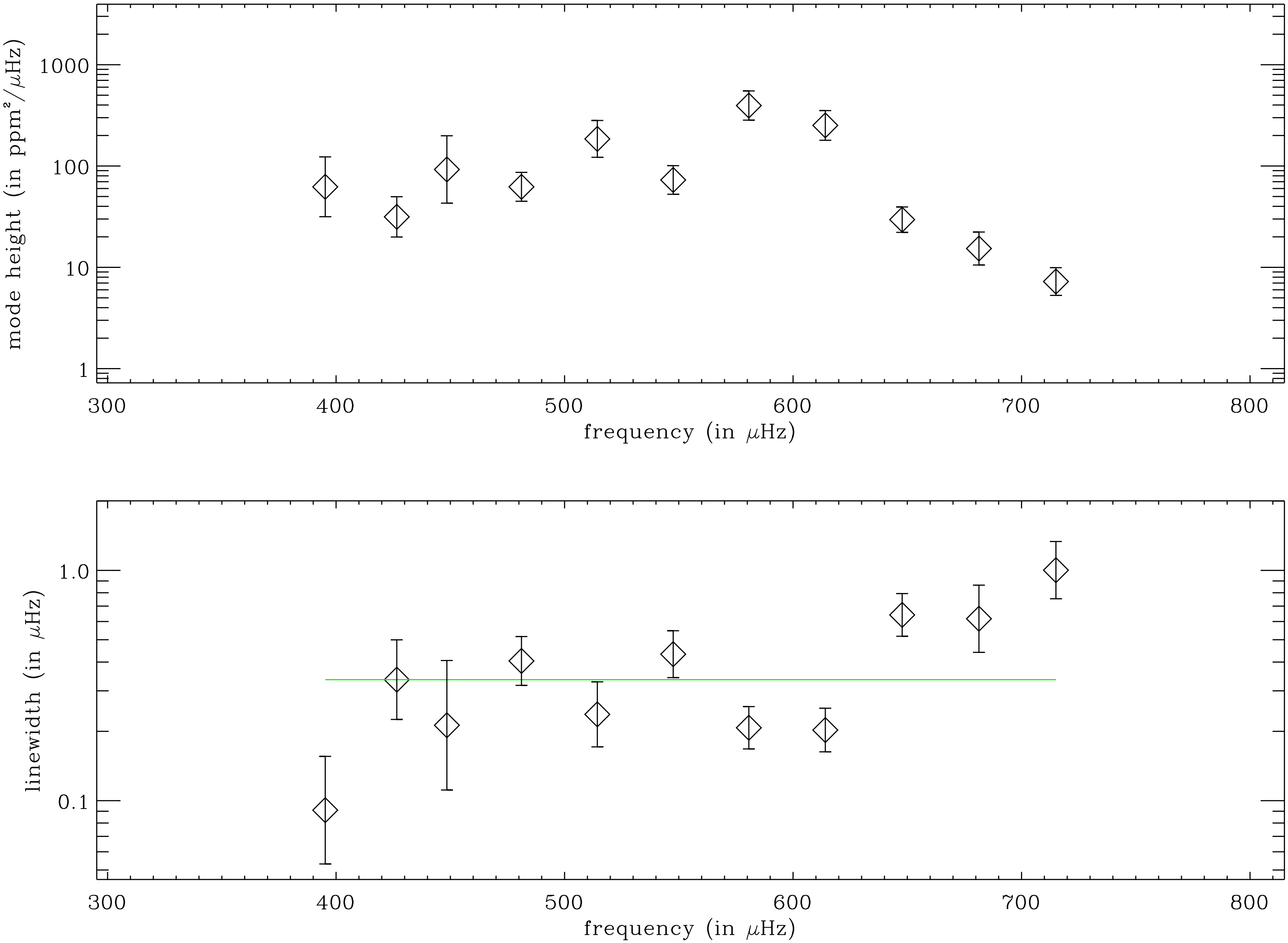
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600
700
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frequency (in μHz)
linewidth (in μHz)
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700
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frequency (in μHz)

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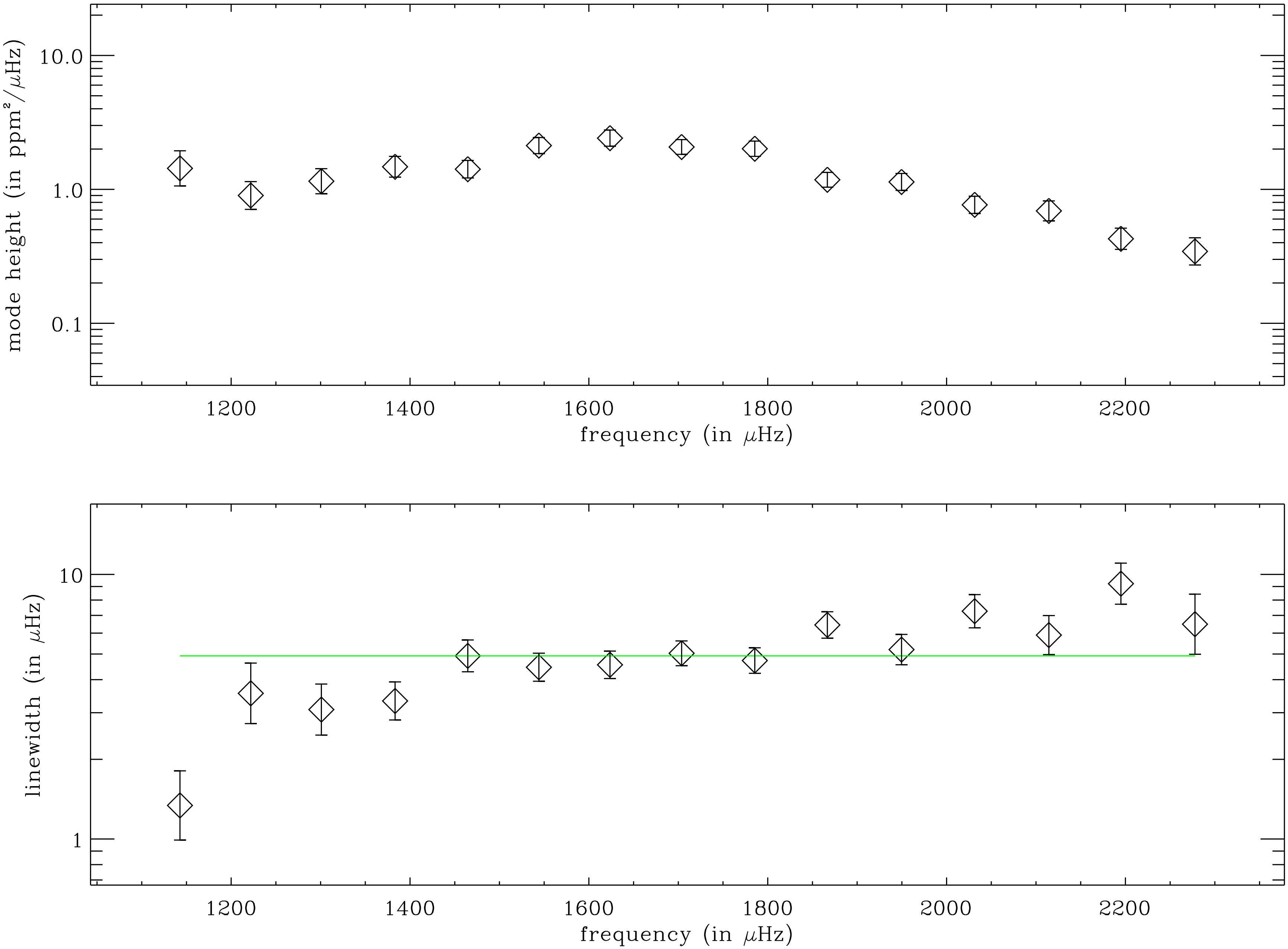

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linewidth (in μHz)
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1600
1800
2000
2200
frequency (in μHz)

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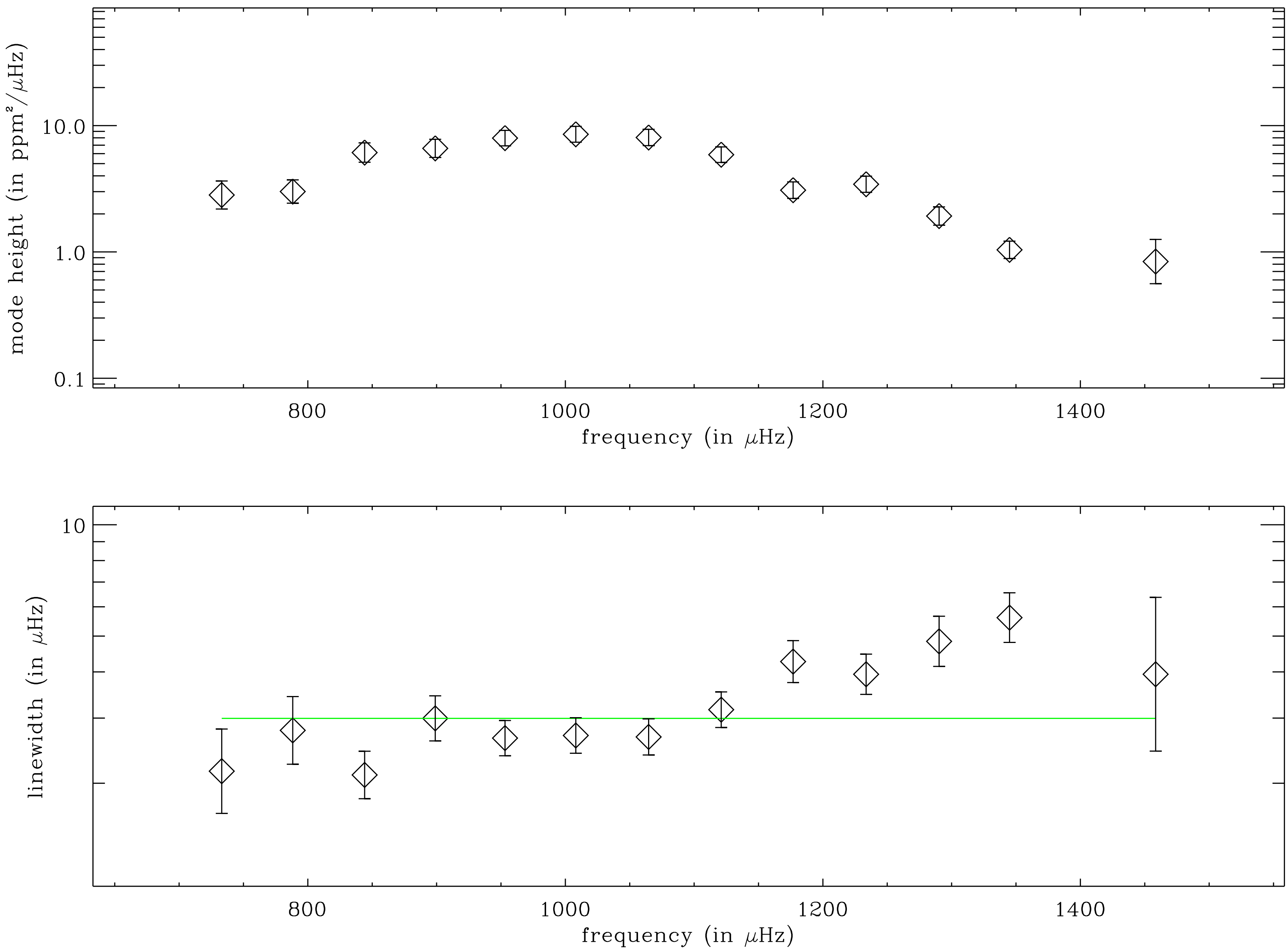

mode height (in ppm²/μHz)
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frequency (in μHz)
10
linewidth (in μHz)
800
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1200
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frequency (in μHz)

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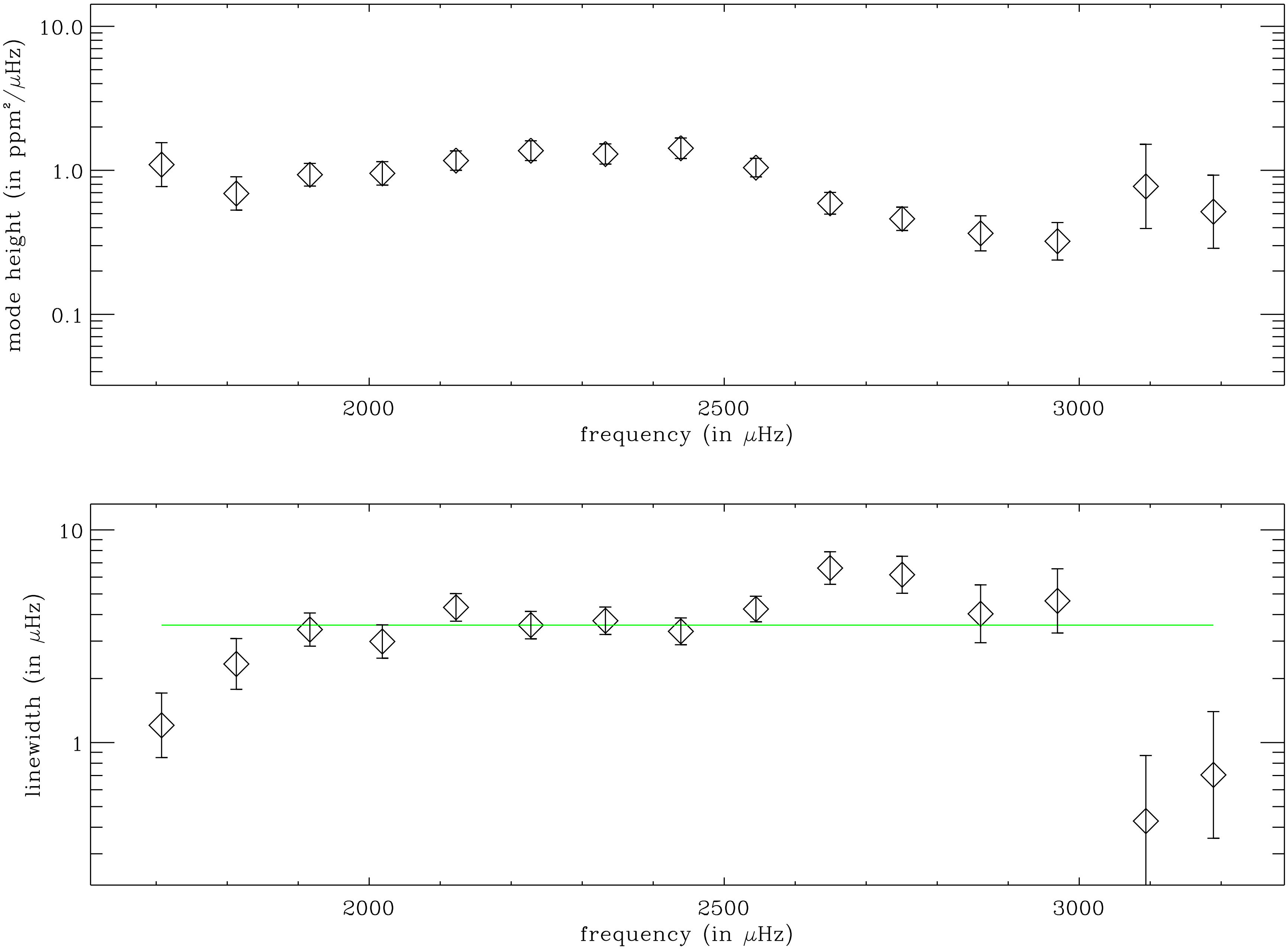
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frequency (in μHz)
linewidth (in μHz)
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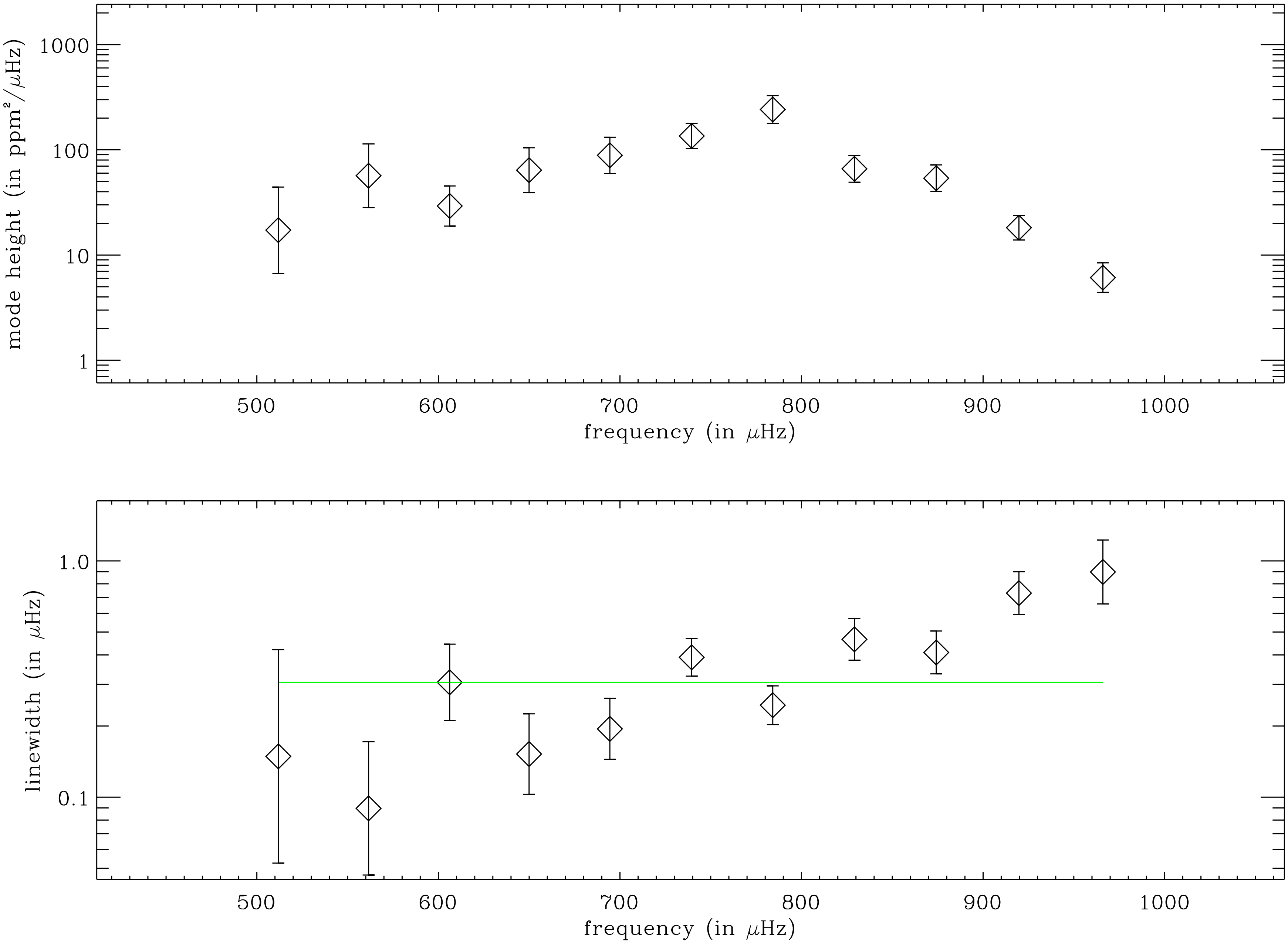
2500
3000
frequency (in μHz)

[redacted]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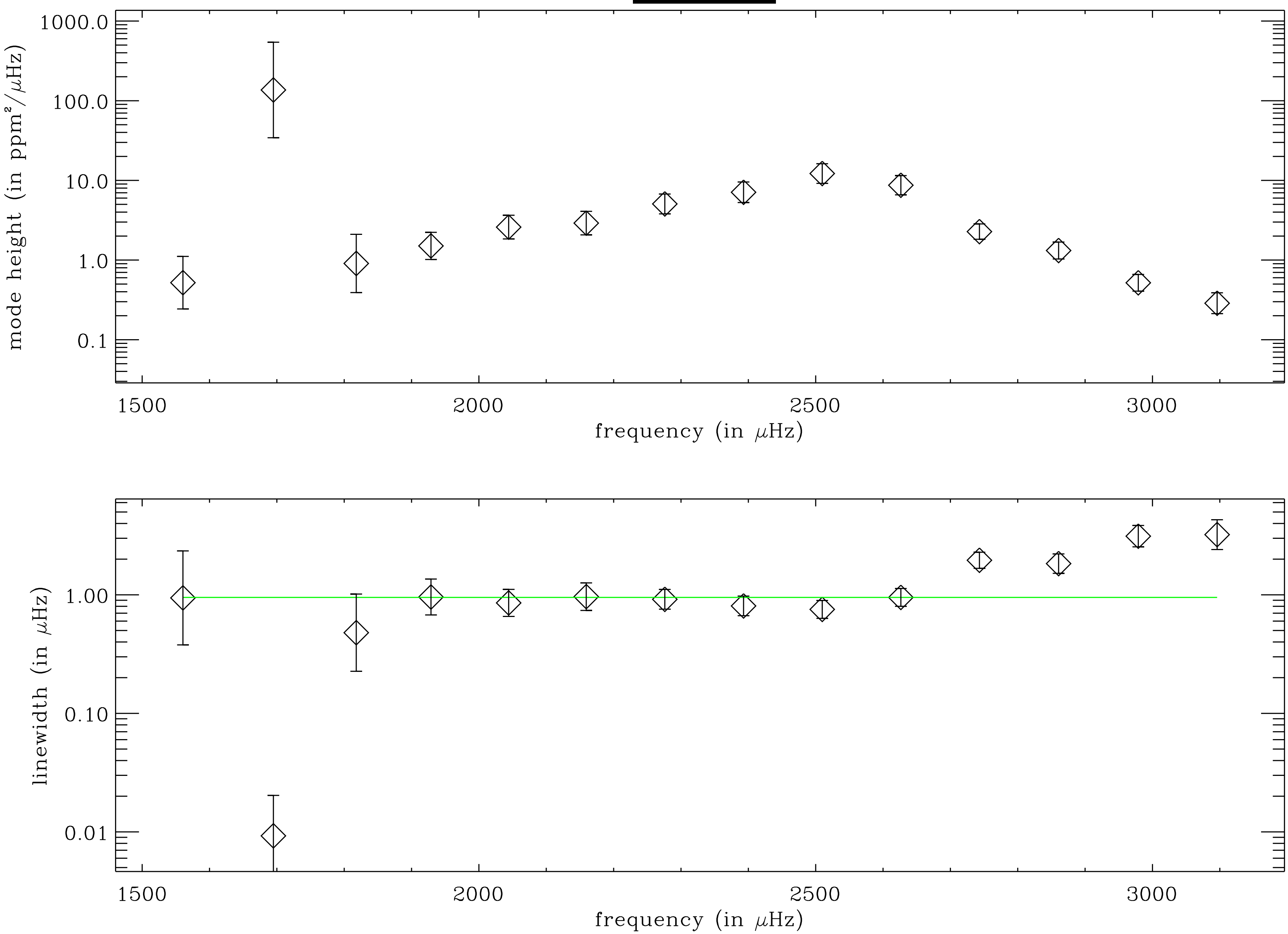
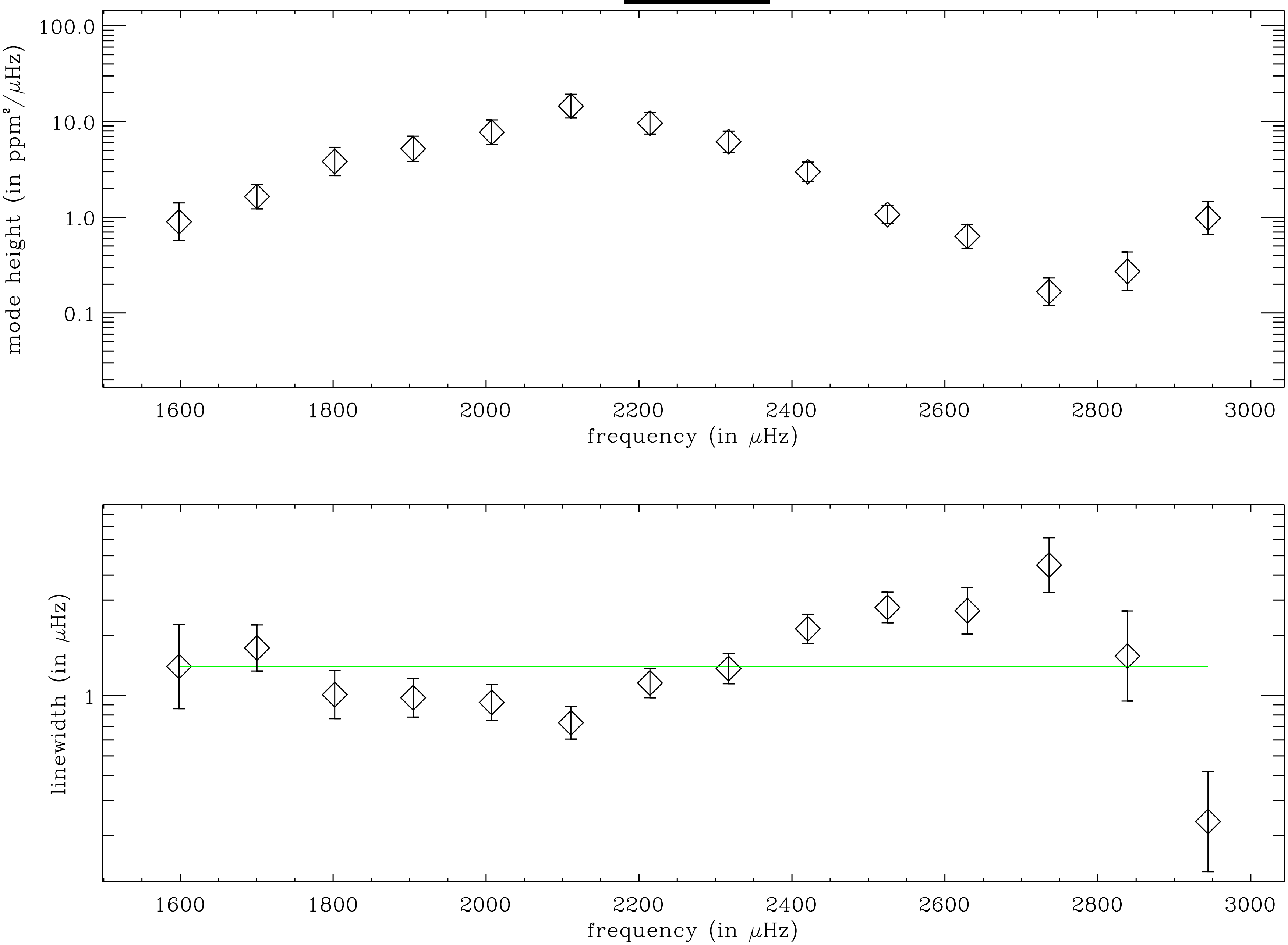
700
800
900
1000
frequency (in μHz)
linewidth (in μHz)
1.0
0.1
500
600
700
800
900
1000
frequency (in μHz)

[redacted]



1000.0
100.0
10.0
1.0
0.1
mode height (in ppm²/μHz)
1500
2000
2500
3000
frequency (in μHz)
1.00
0.10
0.01
linewidth (in μHz)
1500
2000
2500
3000
frequency (in μHz)

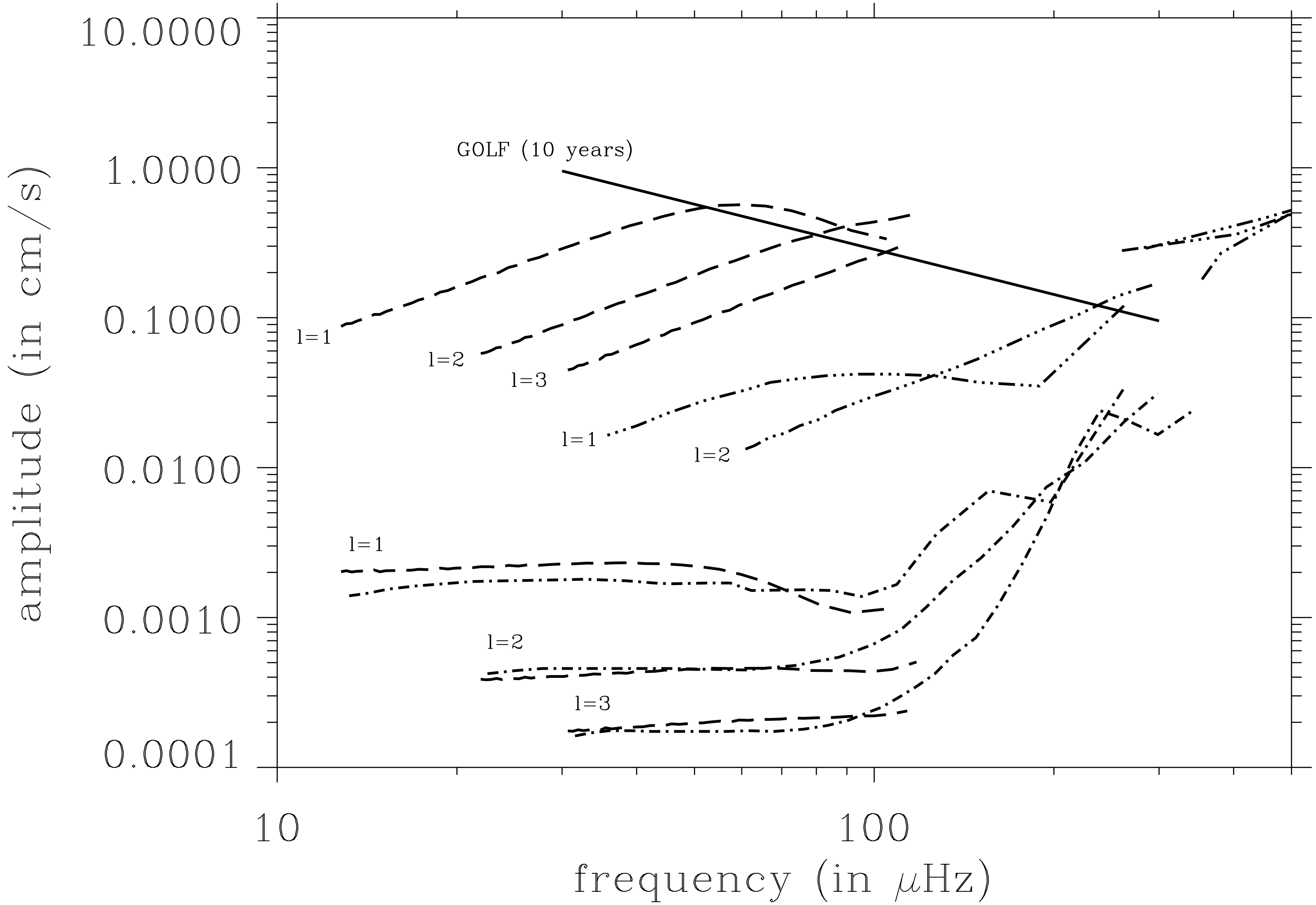
[redacted]



mode height (in ppm²/μHz)
100.0
10.0
1.0
0.1
1600
1800
2000
2200
2400
2600
2800
3000
frequency (in μHz)
linewidth (in μHz)
1
1600
1800
2000
2200
2400
2600
2800
3000
frequency (in μHz)

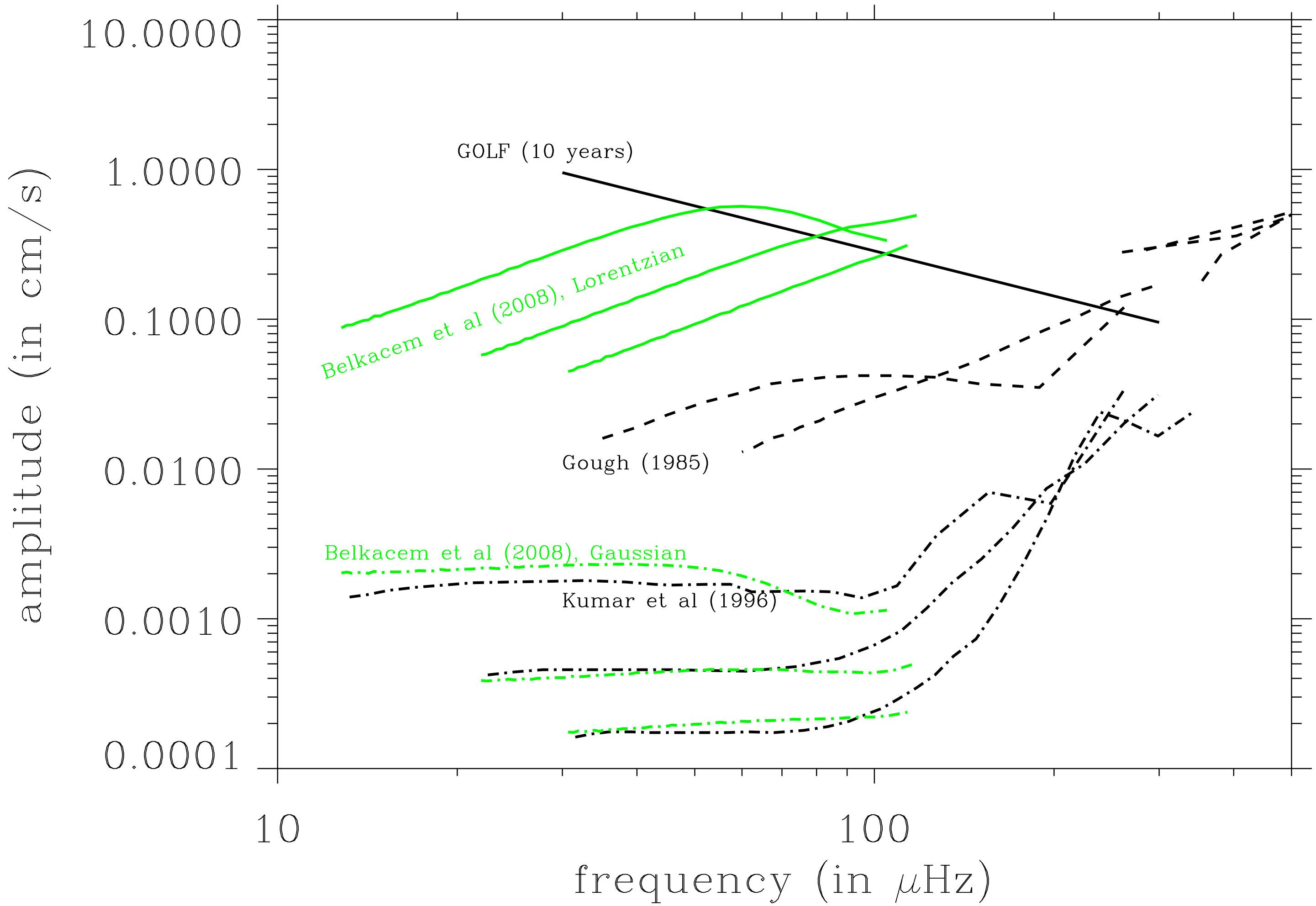
VIRGO and the g-mode search

The Phoebus endeavour

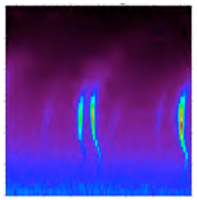


Appourchaux et al (2010)

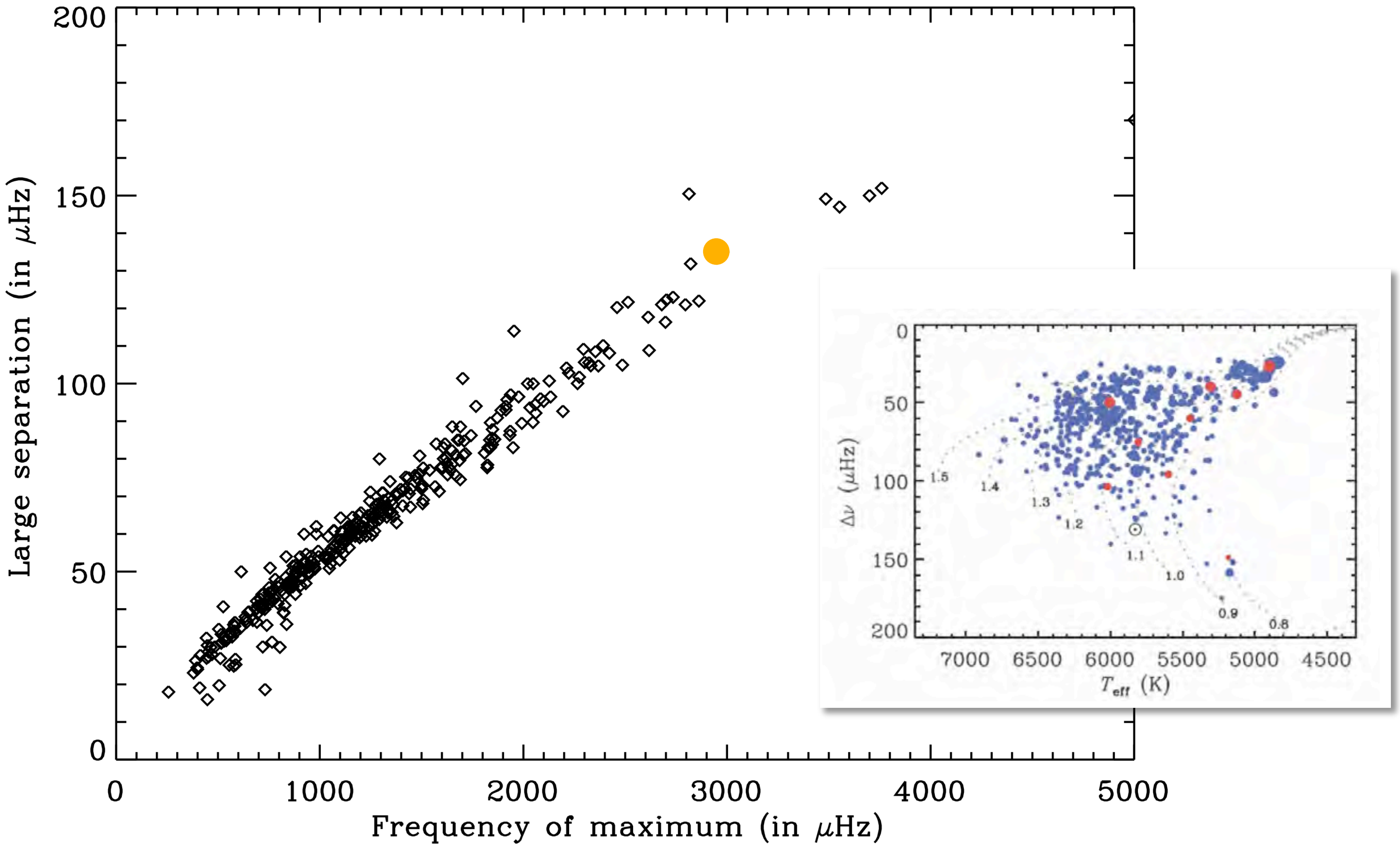
The Phoebus endeavour

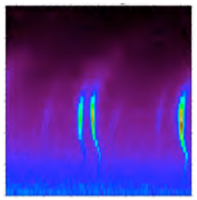


Appourchaux et al (2010)



g-mode search: the future?



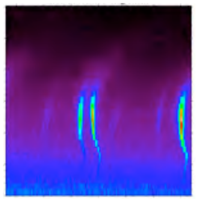


My revisited point of view

In practice, there are *differences* between practice and theory.

In theory there *are none (or a few...)*.

Thank you Douglas !



Convection in Astrophysics

Notes on the 1965

Summer Study Program

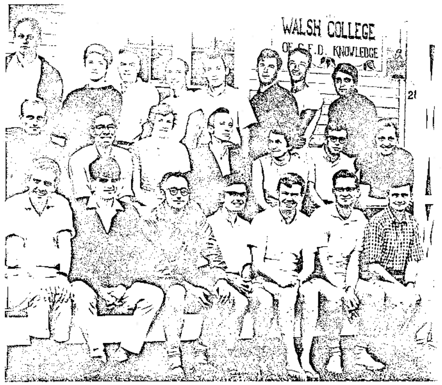
in

GEOPHYSICAL FLUID DYNAMICS

at

The WOODS HOLE OCEANOGRAPHIC INSTITUTION

Reference No. 65-51



The Pulsational Stability of a Convective Atmosphere

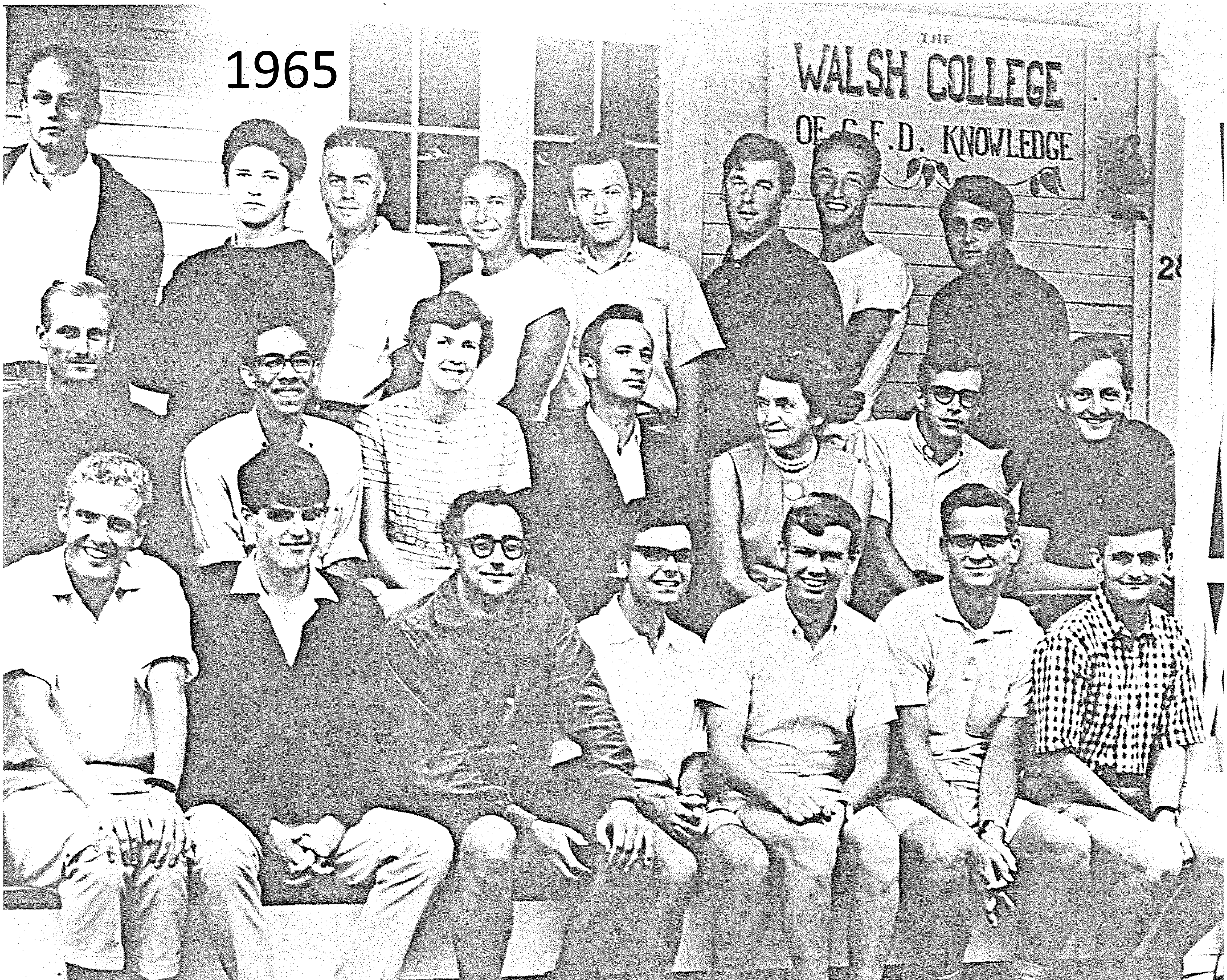
Douglas O. Gough

Introduction

As a star evolves it may pass through phases where it can no longer remain in stable quasi-static equilibrium. The instability arises from the existence of growing oscillatory disturbances (overstability) when the conditions inside the star are favourable. The star then begins to pulsate with increasing amplitude; eventually the structure of the star will be sufficiently changed so that the pulsational mode no longer grows, and the star continues to vibrate with finite amplitude. Recently numerical calculations have been made to determine when a star is pulsationally unstable to infinitesimal radial perturbations (e.g. Baker and Kippenhahn, 1962) but the results do not agree well with observation. There are two major reasons why this could be so. The first is that equilibrium structure about which the perturbation analysis was made may not have been correct, and the second is that convection was disregarded in the stability analysis, although it was taken into account to compute the equilibrium model.

It has been observed that in the computed unstable stars which lie farthest from the observed variable stars, convection plays an increasingly important role in providing the energy flux in the equilibrium model, and it seems likely, therefore, that its neglect in the stability analysis may have led to serious errors. The calcu-

Waves and Physics, Baia della Zaggare


1965
THE
WALSH COLLEGE
OF C.F.D. KNOWLEDGE